

Energy Efficient Channel Access Mechanism for IEEE 802.11ah based Networks

by

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A thesis submitted to the University of London for the
degree of Doctor of Philosophy

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August 2017

TO MY FAMILY

Abstract

IEEE 802.11ah is designed to support battery powered devices that are required to serve for several years in the Internet of Things networks. The Restricted Access Window (RAW) has been introduced in IEEE 802.11ah to address the scalability of thousands of densely deployed devices. As the RAW sizes entail the consumed energy to support the transmitting devices in the network, hence the control mechanism for RAW should be carefully devised for improving the overall energy efficiency of IEEE 802.11ah.

This thesis presents a two-stage adaptive RAW scheme for IEEE 802.11ah to optimise the energy efficiency of massive channel access and transmission in the uplink communications for highly dense networks. The proposed scheme adaptively controls the RAW sizes and device transmission access by taking into account the number of devices per RAW, retransmission mechanism, harvested-energy and prioritised access. The scheme has four completely novel control blocks:

- RAW size control that adaptively adjusts the RAW sizes according to different number of devices and application types in the networks.
- RAW retransmission control that improves the channel utilisation by retransmitting the collided packets at the subsequent slot in the same RAW.
- Harvested-energy powered access control that adjusts the RAW sizes with the consideration of the uncertain amount of harvested-energy in each device and channel conditions.
- Priority-aware channel access control that reduces the collisions of high-priority packets in the time-critical networks.

The performance of the proposed controls is evaluated in Matlab under different net-

work scenarios. Simulation results show that the proposed controls improve the network performances in terms of energy efficiency, packet delivery ratio and delay as compared to the existing window control.

Acknowledgments

I would like to express my sincere gratitude to my primary supervisor, Dr. Kok Keong (Michael) Chai for his continuous support and persistent encouragement during my Ph.D. study and research. His priceless guidance and advice helped me to go through the difficulties. He guided me through the research and writing of this thesis with his patience, motivation, encouragement, enthusiasm, and immense knowledge.

I would like to express my appreciation to Prof. Yue Chen and Dr. John Schormans, for their insightful comments, valuable discussions, and helpful suggestions on technical development and writing skills, which are indispensable for my research progress.

I wish to extend my gratitude to all the colleagues and friends, who have encouraged me and shared the time with me that made the past three years so memorable, Dr. Yun Li, Dr. Dan Zhao, Dr. Lifeng Wang, Dr. Yansha Deng, Dr. Xinyue Wang, Dr. Dantong Liu, Dr. Liumeng Song, Dr. Aini Li, Dr. Yuanwei Liu, Dr. Jingjing Zhao, Dr. Anqi He, Dr. Yuan Ma, Jie Deng, Xingjian Zhang, Bingyu Xu, Yuhang Dai, Xiangyu He, Chao Liu, Zixiang Ma, Xiaoshuai Zhang, Bizhu Wang among others. Many thanks are given to all the support staff at Queen Mary.

At last, I would like to express my gratitude to my parents and boyfriend, in particular, for their enormous love and support in all the important moments of my life. They always be my strongest power to work hard and get through hard time. Without their love, I would not have made it through.

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List of Abbreviations

ACK	Acknowledgement
AID	Associated IDentifier
AP	Access Point
AWGN	Additive White Gaussian Noise
BPSK	Binary Phase Shift Keying
CAS	Channel Access Slot
CSMA/CA	Carrier-Sense Multiple Access with Collision Avoidance
DIFS	Distributed Inter-Frame Space
DL MU-MIMO	Downlink Multi-User Multiple Input Multiple Output
DSSS	Direct-Sequence Spread Spectrum
eNodeB	Evolved Node B
FCC	Federal Communications Commission
IE	Information Element
IoT	Internet of Things
ISM	Industrial Scientific Medical
LAN/MAN	Local and Metropolitan Area Networks
LTE	Long Term Evolution
MAC	Media Access Control
MIMO	Multiple Input Multiple Output
M2M	Machine-to-Machine

OFDM	Orthogonal Frequency Division Multiplexing
PS-poll	PowerSave-poll
QoS	Quality of Service
RAW	Restricted Access Window
RF	Radio Frequency
RFID	Radio-frequency IDentification
RPS	RAW Parameter Set
SIFS	Short Inter-Frame Space
TBTT	Target Beacon Transmission Time
TGah	IEEE 802.11ah Task Group
TIM	Traffic Indication Map
UHF	Ultra High Frequency
U-NII	Unlicensed National Information Infrastructure
VHF	Very High Frequency
WLAN	Wireless Local Area Network

Notations

α	Parameter indicating traffic
AID	Association IDentifier of devices
β	Parameter related to overall number of devices
B	Bandwidth
BER	Bit error rate
c	Index of priority
C	Number of priority classes
\overline{C}	Bit rate
ε_{thr}	Energy threshold
E_c	Energy consumption for collision
$E_{overall}$	Overall energy consumption
E_{signal}	Energy consumption for signalling information
E_t	Transmitting energy consumption
E_{t1}	Energy consumption for Case 1
E_{t2}	Energy consumption for Case 2
$E_{t_{avg}}$	Average energy consumption to send a packet successfully in a slot
E_{wake_up}	Energy consumption for idle listening
EE	Energy efficiency
f	Carrier frequency
F	Noise figure

F_{offset}	Offset parameter to improve fairness
γ	Packet size
g	Index of devices
G_{RX}	Antenna gains at the receiver
G_{TX}	Antenna gains at the transmitter
i	Number of devices in one slot
j	Index of RAW
k	Index of time slot in one RAW
k_b	Boltzmann's constant
l	Distance between device and AP
L_{RX}	System losses at the receiver
L_{TX}	System losses at the transmitter
M	Number of time slots in one RAW
N	Number of devices in one group
\bar{N}	Received noise power
\bar{N}_0	Thermal noise power density
n_c	Number of devices of cth priority class
n_k	Number of devices to choose the kth time slot
P	Transmission probability
P_1	Transmission probability as Case 1
P_2	Transmission probability as Case 2
$P_{2.1}$	Transmission probability as Case 2.1
$P_{2.2}$	Transmission probability as Case 2.2
$P_{back-off}$	Probability of accessing through first back-off stage
$\bar{P}_{consume_j}$	Energy consumption during jth RAW
$\bar{P}_{g-(j-1)}$	Energy level at the end of $(j-1)th$ RAW
$\bar{P}_{harvest_j}$	Harvested-energy during jth RAW
\bar{P}_{RX}	Receiver power
\bar{P}_{TX}	Transmitter power

P_{xy}	Probability to transfer from xth slot to yth slot
PER	Packet error rate
$P(i)$	Probability of i devices that choose the same slot
$PL(l)$	Path loss in dB at distance l
R	Throughput
σ	Limitation of the number of devices in one group
s_k	Number of devices accessing channel successfully in kth time slot
s_{k_1}	Number of packets sent as Case 1 in kth time slot
s_{k_2}	Number of packets sent as Case 2 in kth time slot
τ	Time duration of one time slot in RAW
τ_{back_off}	Time duration of one slot in contention window
T_0	Receiver temperature
v	Transmission rate
W_{\min}	Minimal size of contention window

Chapter 1

Introduction

Internet of Things (IoT) is an inter-networking of any object via the Internet. All objects are able to identify themselves to other objects [ASM⁺][APN12][ZBC⁺14]. According to the prediction in [Dru14], the number of objects including sensors, actuators and motes will reach above 40 billion by 2020. All sensors and end devices are usually operated by battery due to the difficulties of directly connecting power-line to them. The battery in these devices is very cumbersome or almost impossible to be replaced due to high volume of devices. Thus energy efficiency is one of the main challenges in IoT networks.

The sensors and devices are usually connected by low-power wireless networking in IoT networks [HGKP13]. The existing wireless communication technologies, such as Radio-frequency IDentification (RFID), ZigBee, or Bluetooth, can not accommodate high number of devices with high throughput over transmission range of 100 meters or more [KLKG15][DMCAM15][OPR⁺13][BGALAGV16]. Regarding this fact, Low Power Wi-Fi is a promising candidate of enabling communications technology for future dense IoT networks, which is standardised by IEEE 802.11ah [A⁺01][Hal].

1.1 Research Motivation

Energy efficiency is one of the most important design considerations due to the fact that most IoT devices are expected to be battery operated. As up to 6000 devices are supported in IEEE 802.11ah standard, channel access of massive devices has become one of the potential issues of IEEE 802.11ah based networks. The channel access challenges of IEEE 802.11ah based networks include:

1. **Adaptivity:** Flexible adaptation is required in many scenarios where both channel conditions and latency constraints vary. In addition, to increase the efficiency of access and transmission, the adaptation should be achieved with little or no control information exchange. As massive access would lead to high collision probability, the adaptive scheme for IEEE 802.11ah based networks is needed to deal with high collisions for highly dense devices.
2. **Channel Utilisation:** Channel utilisation affects the access efficiency, latency and the transmission cost. This is because autonomous systems require timely and effective information exchange in IoT networks.
3. **Energy Harvesting:** Energy harvesting technique has brought the possible solutions for remote sensors to extract energy from ambient environment. However, these energy-harvesting devices pose new challenges due to the uncertain amount of energy that is harvested from the environment.
4. **Priority:** One of the methods to improve access efficiency for time-critical networks is to prioritise the packets. The high-priority packets need to be transmitted timely, which has not been realised in current IEEE 802.11ah. Thus, a prioritised channel access is required in IEEE 802.11ah.

In summary, the critical channel access challenge for IEEE 802.11ah networks lies in facilitating channel access to large number of power limited devices while supporting the diverse performance requirements such as low latency, achievable data rate, energy

harvesting and time-critical.

1.2 Research Scopes and Objectives

This thesis focuses on channel access controls of IEEE 802.11ah based networks. The aim is to optimise the energy efficiency of massive channel access and transmission in the uplink communications. Various network dynamics have been taken into consideration, such as group size, retransmission, energy harvesting and priority.

A two-stage adaptive Restricted Access Window (RAW) scheme for the IEEE 802.11ah based networks is proposed, which consists of four controls:

1. RAW size control aims to address the relationship between the channel access and energy efficiency, and adapt the number of slots and internal slot interval for one RAW to optimise network performance.
2. RAW retransmission control that utilises the next empty slot for retransmission in the uplink aims at reducing the empty slot waste and increasing channel utilisation when attempting accessing, which can improve the energy efficiency and decrease delay for communications.
3. Harvested-energy powered access control aims to change the conventional battery power supply, which can extend network lifetime and increase energy efficiency.
4. Priority-aware channel access control aims at decreasing the collision of high-priority packets to improve the access efficiency and energy efficiency.

1.3 Contributions

A two-stage adaptive RAW scheme is proposed to improve energy efficiency for IEEE 802.11ah. The first-stage is novel RAW size control, and the second-stage includes three novel controls: retransmission control, harvested-energy powered access control and priority-aware channel access control. Hill Climbing, Simulated Annealing and Gradient Descent are applied in this research work. The upper bound of energy efficiency is derived to compare with the energy efficiency of the proposed control.

1. A RAW size control optimisation problem is formulated by probability theory to describe the channel access via RAW in uplink IEEE 802.11ah communications for highly dense IoT networks. Two algorithms are designed in this control: an energy-aware access window algorithm that optimises uplink energy efficiency by identifying the optimal number of slots in one RAW for diverse group sizes; an energy-delay aware window algorithm that jointly optimises uplink energy efficiency and delay by determining the number of slots and internal slot interval for one group of devices.
2. A novel retransmission mechanism is proposed to improve channel utilisation by utilising the subsequent empty slot for collided devices to retransmit in the uplink. For random selection in uplink communications, some slots contain more than one device to attempt accessing, but some contain no device. Motivated by this, novel retransmission mechanism is designed to alleviate the waste of idle slots, which can decrease the idle listening energy consumption and improve the number of transmitted packets in a certain time period.
3. A RAW retransmission control is proposed to improve uplink energy efficiency by adaptive window size based on retransmission mechanism. Two algorithms are designed for this control: an energy-aware access window with retransmission algorithm that optimises uplink energy efficiency by adapting the RAW size according to group size based on retransmission mechanism; an energy-delay aware

access window with retransmission algorithm is proposed to jointly optimise uplink energy efficiency and delay for IoT applications through dynamically estimating the adaptive RAW size and internal slot interval for various groups based on the novel retransmission.

4. A harvested-energy powered access window control is proposed to improve energy efficiency for IEEE 802.11ah networks which are composed of devices powered by harvested-energy. A harvested-energy powered energy-aware access window algorithm is proposed to set adaptive window based on channel conditions and the number of devices that store sufficient energy. In addition, a grouping strategy, as harvested-energy powered energy-aware access window with grouping strategy algorithm, is proposed to cluster devices based on the energy stored in each device and the required data rate.
5. A novel prioritised channel access mechanism is proposed to improve access efficiency for time-critical networks. The proposed mechanism spares more chances for high-priority packets to attempt accessing channel by decreasing the contention and limiting the collisions.
6. A priority-aware channel access control is proposed to optimise energy efficiency and access efficiency. A priority-aware access window algorithm is designed to adapt the RAW size based on the prioritised channel access mechanism for different scenarios as various number of priority classes and diverse priority classification distributions.

1.4 Author's Publication

Y. Wang, K. K. Chai, Y. Chen, J. Schormans, Energy Efficient Window Control Scheme for IEEE 802.11ah (Wi-Fi HaLow) based Networks, accepted by Journal of Electrical Engineering, 2017.

Y. Wang, K. K. Chai, Y. Chen, J. Schormans, J. Loo, Energy-aware Restricted Access Window Control with Retransmission Scheme for IEEE 802.11ah (Wi-Fi HaLow) based Networks, 2017 IEEE/IFIP 13th Wireless On-demand Network systems and Services Conference (WONS), Jackson Hole, Wyoming, USA, 21 - 24 Feb 2017.

Y. Wang, K. K. Chai, Y. Chen, J. Schormans, J. Loo, Energy-Delay Aware Restricted Access Window with Novel Retransmission for IEEE 802.11ah Networks, 2016 IEEE 59th Global Communications Conference (Globecom), Washington, DC USA, December 2016.

Y. Wang, C. Liu, K. K. Chai, Y. Chen, J. Loo, Optimized Energy-aware Window Control for IEEE 802.11ah Based Networks in Smart Grid Enabled Cities, 2016 International Conference on Smart Grid Inspired Future Technologies, Liverpool, UK, May 2016.

Y. Wang, Y. Li, K. K. Chai, Y. Chen, J. Schormans, Energy-aware Adaptive Restricted Access Window for IEEE 802.11ah Based Smart Grid Networks, 2015 IEEE International Conference on Smart Grid Communications (SmartGridComm), Miami, FL, USA, November 2015.

Y. Wang, Y. Li, K. K. Chai, Y. Chen, J. Schormans, Energy-aware Adaptive Restricted Access Window for IEEE 802.11ah Based Networks, 2015 IEEE 26th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Hong Kong, China, August 2015.

C. Liu, K. K. Chai, E. T. Lau, Y. Wang, Y. Chen, Optimised Electric Vehicles Charging Scheme with Uncertain User-Behaviours in Smart Grids, 2017 IEEE 28th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Montreal, QC, Canada, October 2017.

1.5 Thesis Structure

This thesis is organised as follow.

Chapter 2 introduces the characteristics and Media Access Control (MAC) layer features of IEEE 802.11ah, shows the methodologies applied in this thesis, as well as summarises current state-of-the-art of channel access in IEEE 802.11ah, harvested energy powered MAC and prioritised MAC.

Chapter 3 introduces the proposed adaptive RAW scheme framework, and presents the RAW size control for IEEE 802.11ah networks to improve uplink energy efficiency as well as delay by identifying the number of slots and internal slot intervals in each RAW for different groups. The simulation results of the proposed control and its performance analysis are given under the comparison with the existing RAW control.

Chapter 4 presents the retransmission control for IEEE 802.11ah networks to improve channel utilisation. It begins with a new retransmission mechanism for IEEE 802.11ah to utilise the RAW empty slots during random selection. Based on that, two adaptive algorithms are proposed to adapt RAW size to optimise network performance. The performance of proposed control is evaluated via simulations.

Chapter 5 focuses on the harvested-energy powered access control for IEEE 802.11ah networks to maximise uplink energy efficiency by dynamically adjusting RAW with the joint consideration of RAW duration, channel condition and harvested-energy. The performance evaluation is carried out for the proposed control.

Chapter 6 investigates priority-aware channel access control for IEEE 802.11ah based time-critical networks. It begins with a proposed prioritised channel access mechanism to support the priority in IEEE 802.11ah to improve the access efficiency. Based on that,

a priority-aware channel access control is proposed to improve energy efficiency through adaptive window size. The performance evaluation provides guidelines on adaptive window size policy design for the priority-aware scenarios.

Chapter 7 gives conclusions of the thesis, and the idea about future work is also presented.

Chapter 2

Background and State-of-the-art

Future applications and services of scalable smart systems such as grids, factories, and cities require dense smart components such as sensors, robots, controllers to connect together, which is called IoT. Increasing adoption of IoT applications indicates that the population of sensors that are presenting within a specific geographic area is increased rapidly. Generally, the IoT devices have the characteristics of low memory, reduced battery capacity, reduced processing capabilities and vulnerable radio conditions.

This chapter presents the introduction of the IEEE 802.11ah key mechanism and current research on channel access for IEEE 802.11ah based networks. Special focus is given to the energy efficient channel access management solution for IEEE 802.11ah based IoT networks. Section 2.1 describes the physical layer and MAC layer features of IEEE 802.11ah. In the Section 2.2, the basics of the relevant methodologies used in this thesis are presented. Section 2.3 presents a study of state-of-the-art channel access for IEEE 802.11ah, energy harvesting networks and time-critical networks.

2.1 IEEE 802.11ah

2.1.1 IEEE 802.11 Family

IEEE 802.11 family is a series of standard of physical and MAC layer, mainly for wireless local area networks communications, which is created and maintained by IEEE Local and Metropolitan Area Networks (LAN/MAN) standards committee [CWKS97]. The IEEE 802.11 was the first one to be released in June 1997. Subsequently, multiple sets of standards for various operating frequencies have been proposed such as IEEE 802.11a, IEEE 802.11b, IEEE 802.11g, IEEE 802.11n, IEEE 802.11ac, IEEE 802.11ad, IEEE 802.11af and IEEE 802.11ah for diverse applications with various transmission ranges under 54 MHz to 60 GHz frequency band [SCS]. Fig. 2.1 shows various IEEE 802.11 standards in relation to the operation frequency and maximum transmission range. The main characteristics for IEEE 802.11 family are listed in Table 2-A.

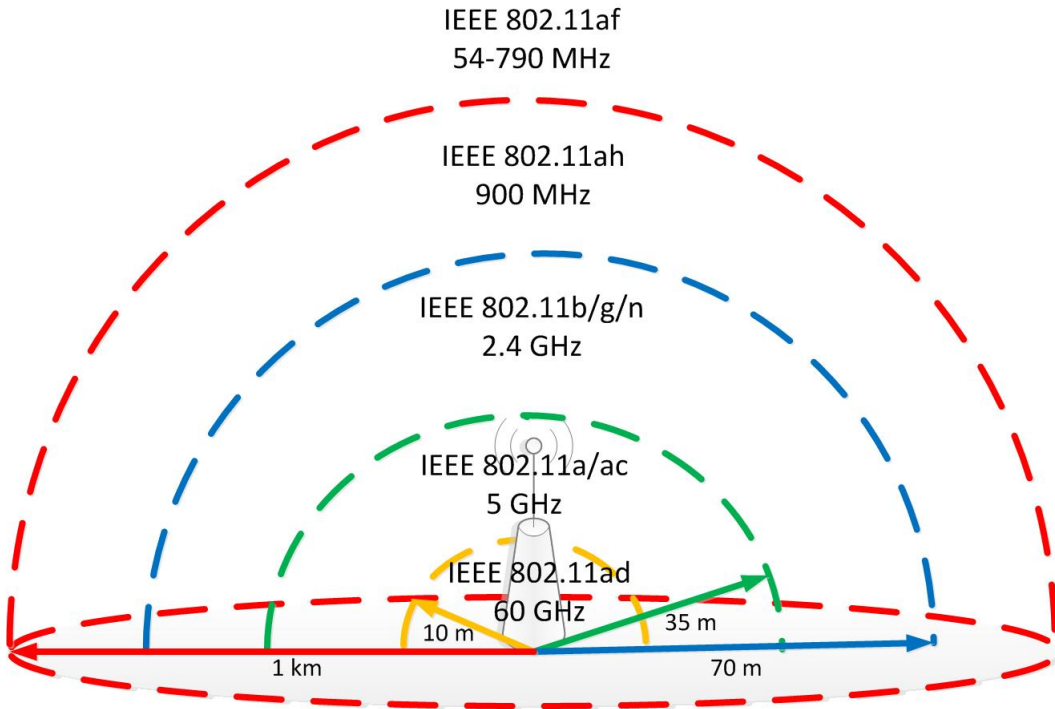


Fig. 2.1: IEEE 802.11 family [SCS][MSP16][MII⁺17][APN15].

Table 2-A: IEEE 802.11 Family Comparison [AMO15][SCS][APN15]

Standard	Frequency Band	Bandwidth	Modulation Scheme	Maximum Data Rate	Range
IEEE 802.11	2.4 GHz	22 MHz	BPSK to 256-QAM	2 Mbps	20 m
IEEE 802.11b	2.4 GHz	21 MHz	BPSK to 256-QAM	11 Mbps	35 m
IEEE 802.11a	5 GHz	22 MHz	BPSK to 256-QAM	54 Mbps	35 m
IEEE 802.11g	2.4 GHz	23 MHz	BPSK to 256-QAM	54 Mbps	70 m
IEEE 802.11n	2.4 GHz	24 MHz and 40 MHz	BPSK to 256-QAM	600 Mbps	70 m
IEEE 802.11ac	5 GHz	20, 40, 80, 160 MHz	BPSK to 256-QAM	6.93 Mbps	35 m
IEEE 802.11ad	60 GHz	2.16 MHz	BPSK to 64-QAM	6.76 Mbps	10 m
IEEE 802.11af	54-790 MHz	6, 7 and 8 MHz	BPSK to 256-QAM	26.7 Mbps	>1 km
IEEE 802.11ah	900 MHz	1, 2, 4, 8 and 16 MHz	BPSK to 256-QAM	40 Mbps	1 km

The operating frequency for IEEE 802.11b and IEEE 802.11g is 2.4 GHz Industrial Scientific Medical (ISM) band. Due to frequency band, IEEE 802.11b and IEEE 802.11g equipment may occasionally suffer the interference from microwave ovens, cordless telephones, and Bluetooth devices [AC01]. To address this issue, Direct-Sequence Spread Spectrum (DSSS) and Orthogonal Frequency Division Multiplexing (OFDM) signalling methods are used to control interference and susceptibility to interference in IEEE 802.11b and IEEE 802.11g [ZTJ⁺04]. The IEEE 802.11n standard is another standard operating at 2.4 GHz, where Multiple Input Multiple Output (MIMO) is applied to increase the range and throughput for wireless networks. The IEEE 802.11a standard operates at 5 GHz Unlicensed National Information Infrastructure (U-NII) band, which provides at least 23 non-overlapping channels rather than the 2.4 GHz ISM frequency band with adjacent channels overlap [ZCPN13]. IEEE 802.11ac utilises the operating frequency of 5 GHz with less prone to interference when compared with IEEE 802.11 b and g [PRPF15] [JS15]. For IEEE 802.11n, there is more interference under operating with 2.4 GHz, while less interference under operating with 5 GHz, which is similar to IEEE 802.11ac standard [Xia05]. IEEE 802.11ad operates in the 60 GHz millimetre wave spectrum, where it consists of four channels as each 2.16 GHz wide with centre frequencies of 58.32, 60.48, 62.64, and 64.80 GHz [NCF⁺14]. IEEE 802.11af allows Wireless Local Area Network (WLAN) operation in TV white space spectrum in the Very High Frequency

(VHF) and Ultra High Frequency (UHF) bands between 470790 MHz in Europe and non-continuous 54698 MHz in the United States by cognitive radio technology to transmit on unused TV channels, with the standard taking measures to limit interference for primary users, such as analogue TV, digital TV, and wireless microphones [FGK⁺13]. IEEE 802.11ah defines a WLAN system operating at sub-1 GHz license-exempt bands to provide an improved transmission range compared with the conventional IEEE 802.11 WLANs operating in the 2.4 GHz and 5 GHz bands [KLKG15].

The segment of the radio frequency spectrum for IEEE 802.11 is different between countries. In the US, IEEE 802.11a and IEEE 802.11g devices may be operated without a license. Frequencies used by channels one through six of IEEE 802.11b and g fall within the 2.4 GHz amateur radio band [CCG98]. Licensed amateur radio operators may operate IEEE 802.11b and g devices under Part 97 of the Federal Communications Commission (FCC) Rules and Regulations, allowing increased power output but not commercial content or encryption [C⁺07].

IEEE 802.11ah defines a WLAN system to support highly dense networks. IEEE 802.11ah can be used for various purposes including large scale sensor networks, extended range hotspot, and outdoor Wi-Fi for cellular traffic offloading, whereas the available bandwidth is relatively narrow [SCC13].

2.1.2 IEEE 802.11ah

IEEE 802.11ah operates at sub-1 GHz ISM band and it can support up to 6000 devices within a network with the transmission range up to 1 km at the rate of more than 100kbps [HRV12][ABB⁺14]. The standardisation work started in November 2010 [A⁺01]. This technology is envisaged to be used in the smart grid, consumer electronics and health-care. The features of Low Power Wi-Fi includes the methodology used in target wake time to inform devices when to wake up and header overhead reductions [APN15].

One of the goals of IEEE 802.11ah Task Group (TGah) is to offer a standard that, apart from satisfying these previously mentioned requirements, minimises the changes with respect to the widely adopted IEEE 802.11. In that sense, the proposed physical and MAC layers are based on the IEEE 802.11ac standard and moreover, try to achieve an efficiency gain by reducing some control/management frames and the MAC header length.

In 2010, having studied the sub-1 GHz license-exempt bands (except for TV white spaces), IEEE LAN/MAN standards committee determined this spectrum to be promising for outdoor communication of IEEE 802.11 devices. Because of the scarcity of the available spectrum, sub-1 GHz does not allow using wide bands, especially ≥ 20 MHz wide bands introduced in IEEE 802.11n and ac. Nevertheless, the novel modulation and coding schemes, designed in the IEEE 802.11ac amendment and brought to IEEE 802.11ah, can provide hundreds Mbps if channel conditions are good enough. At the same time, sub-1 GHz frequencies have better propagation characteristics in outdoor scenarios than traditional for Wi-Fi 2.4 and 5 GHz bands, which increases transmission range up to 1 km.

The IEEE 802.11ah physical layer is inherited from IEEE 802.11ac and adopted to available sub-1 GHz bandwidth. The channels used in IEEE 802.11ah are 10 times narrower than those in IEEE 802.11ac: 1, 2, 4, 8 and 16 MHz, shown in Fig. 2.2, of which only 1 and 2 MHz channels are mandatory. Technologies like OFDM, MIMO and Downlink Multi-User MIMO (DL MU-MIMO) which was firstly introduced in the IEEE 802.11ac, are also employed by the IEEE 802.11ah system [Par15].

2.1.3 MAC Layer of IEEE 802.11ah

IEEE 802.11 MAC layer defines that the Access Point (AP) assigns an Association Identifier (AID) to each device. The maximum number of devices mapped is only 2007, due

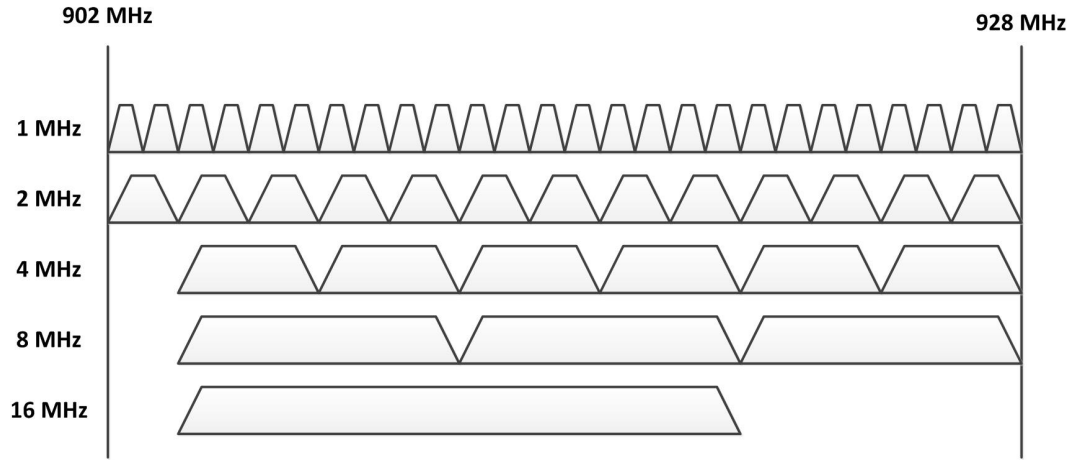


Fig. 2.2: US IEEE 802.11ah channel [KLKG15].

to the length of the partial virtual bitmap of Traffic Indication Map (TIM) Information Element (IE). In order to support a larger number of devices, TGah has defined a novel and hierarchical distribution of them [ABB⁺13]. With this novel structure, the IEEE 802.11ah achieves the objective of supporting up to 6000 devices. In this manner, the AIDs are classified into pages, blocks, sub-blocks and device indexes. The number of pages and blocks per page is configurable according to the size and requirements of the network. The IEEE 802.11ah AID is unique and consists of 13 bits that include the different hierarchical levels. It can be an effective way to categorise devices with respect to their type of application, battery level or required Quality of Service (QoS).

2.1.3.1 Distributed Channel Access

It is the basic random access MAC protocol of IEEE 802.11 standard that includes Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) [KACD17]. Furthermore, it encompasses binary exponential back-off rules to manage the retransmission of collided packet [SD15]. It works as follows. Before initiating a transmission, a device senses the channel to determine whether it is busy. If the medium is sensed idle during a period of time called the Distributed Inter-Frame Space (DIFS), the device is allowed to transmit [CLW16]. If the medium is sensed busy, the transmission is delayed until

the channel is idle again. In this case, a slotted binary exponential back-off interval is uniformly chosen in $[0, CW-1]$, where CW is the contention window [SLC13]. After each data frame is successfully received, the receiver transmits an acknowledgement (ACK) frame after a Short Inter-Frame Space (SIFS) period [ZNC⁺14].

2.1.3.2 Restricted Access Window

To decrease collision probability in networks with thousands of devices and thus to improve power efficiency, TGah has developed RAW. The key idea of RAW is to limit the number of devices contending within the window that consists of equal time slots [KC17].

By broadcasting in beacons special RAW Parameter Set (RPS) IEs, the AP allocates one or more restricted channel access intervals as RAW. All devices in this network listen in the beginning of beacon frame called Target Beacon Transmission Time (TBTT) to obtain scheduling information that indicates which RAW they belong to. Subsequently, devices would fall into sleep mode until turning to their allocated RAW to attempt to access [ABB⁺14]. During RAW, only a set of devices determined by the lowest and the highest AIDs, both from the same page, can access the channel [ABB⁺13].

Each RAW consists of equal time slots corresponding to various devices as shown in Fig. 2.3. Due to the frame format, if the number of slots in one window is less than 8, each slot may reach 246.14 ms. Otherwise, the slot duration is limited to 31.1 ms. During RAW, each device is forbidden to access the channel before its slot.

For uplink communications, the devices randomly choose a slot in the allocated window to attempt to access the channel. For downlink communications, the devices are assigned with a slot in the window to receive the packet from AP, which is calculated as

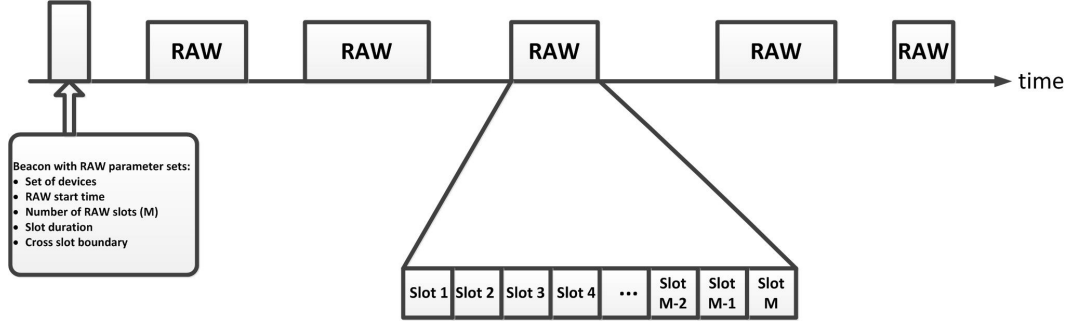


Fig. 2.3: RAW internal structure.

follows:

$$k = (AID + F_{offset}) \bmod M, \quad (2.1)$$

where k is the index of time slot. AID is AID of devices. F_{offset} is an offset parameter to improve fairness. M is the total number of time slot in one RAW. For example, if F_{offset} is 2, one device with AID numbered 6 would be allocated to the 8th slot of a RAW containing 50 time slots [RPH⁺14].

For the internal time slot operation, CSMA/CA is applied for all the devices in this slot. The devices sense the channel to check whether there is other devices in the same slot. When there are multiple devices in one slot, these devices go to back-off stage to avoid collision by randomly choosing one of slots in contention window. The first device who sends a request to AP can access channel, while the others need to re-attempt in another allocated RAW. If no device can build connection with AP via the first back-off stage, all the devices in the slot go to second back-off stage via a double-size contention window, and same for the latter stages. One example is shown in Fig. 2.4, Device 1 and Device 3 sense that the channel is not idle, and then both of them go to first back-off stage by choosing one slot in contention window that consists of 8 slots. As Device 1 establishes the communication with AP at 3rd slot of contention window, Device 3 needs to re-attempt in subsequent allocated RAW. In Slot 2, Device $N(j) - 2$ and Device $N(j)$ collide at 7th slot in first contention window, so they need to re-select slot in second contention window with 16 slots. For the uplink communications, if accessing the channel

successfully, device requests uplink communications by sending a PowerSave-poll (PS-poll) message to the AP. The AP responds with an ACK to confirm the connection. After the first handshake, the device transmits buffered uplink data frame and waits for the ACK from the AP after a SIFS period[Par13].

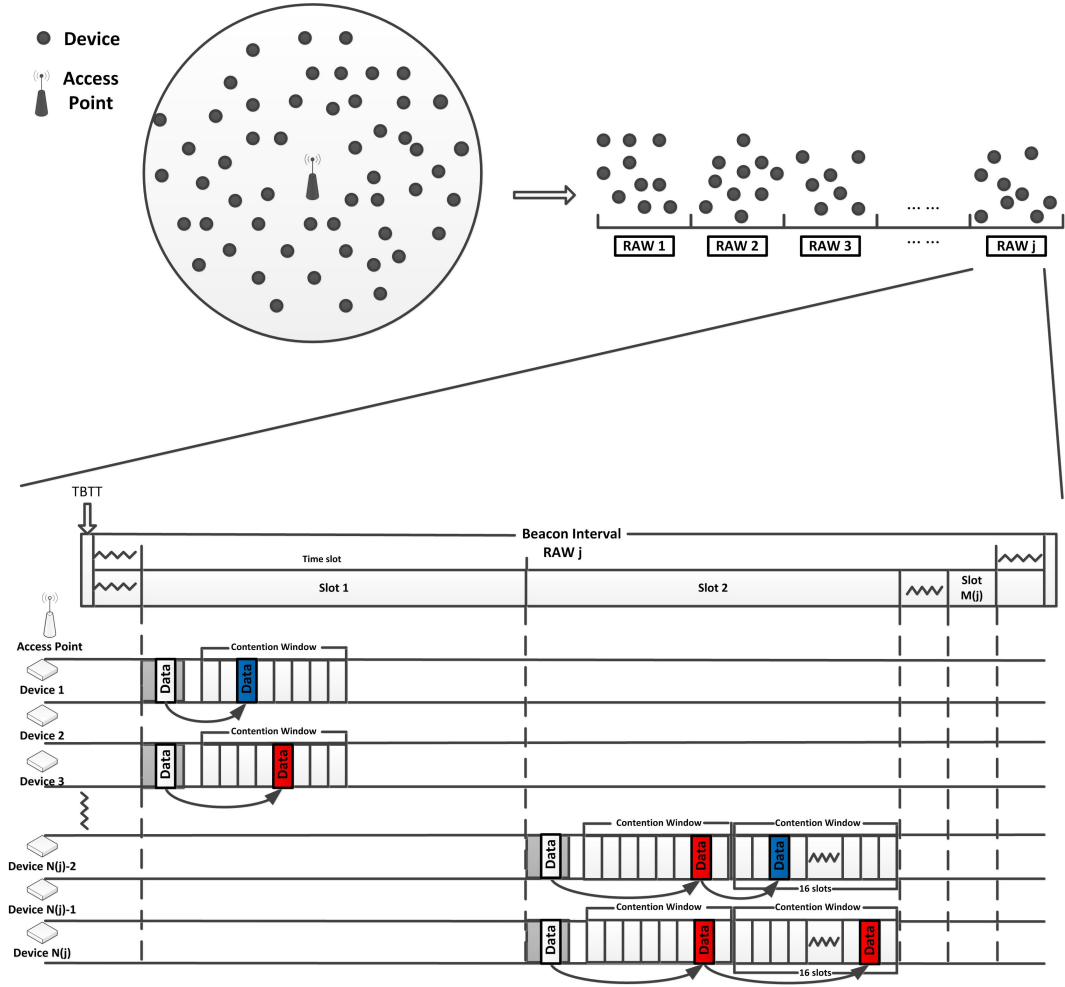


Fig. 2.4: RAW internal operation [PHL14].

The AP optionally allows devices to exceed their slots (Cross Slot Boundary) when transmitting or counting down back-off. However, in this case, devices that wake up at the beginning of the next slot should wait until packet exchange ends or the channel is free for the Probe Delay interval before starting contention. If the AP does not allow to Cross Slot Boundary in RAW, devices may awake at the beginning of their slots and

start contending for the channel immediately. Although restriction of Cross Slot Boundary provides fair resource allocation (the devices from the first slot do not contend in next slots), it may lead to the waste of channel resources when the slot is not ended yet but the remaining part is not enough for the whole packet transmission. It results in non-monotonic dependence of throughput on slot duration without Cross Slot Boundary [ZNC⁺14].

2.2 Optimisation Methodology

This section shows the introduction of relevant methodologies used in this thesis to solve the massive access optimisation problem for IEEE 802.11ah based networks. The mentioned methodologies as Hill Climbing, Simulated Annealing and Gradient Descent are described.

2.2.1 Hill Climbing

Hill Climbing is an iterative mathematical optimisation technique for local search. It is suitable for finding a local optimum but it is not necessarily guaranteed to find the global optimum out of all search space [GQT66]. The characteristic that only local optima is guaranteed can be solved by using restarts (i.e. repeated local search). It can also be solved by using more complex schemes based on iterations, like iterated local search, based on memory, like reactive search optimisation and Tabu search, or based on memory-less stochastic modifications, like Simulated Annealing [LRZ06]. But the optimal solution could be obtained in convex problems [OAM03].

The simplicity of this algorithm makes it popular for optimisation problems such as in artificial intelligence, although more advanced algorithms such as simulated annealing may give better results. Hill Climbing can often produce a better result than other algorithms when the amount of time available to perform a search is limited, such as with

real-time systems. It is an any-time algorithm: it can return a valid solution even if it is interrupted at any time before it ends [GG03].

Hill Climbing starts with an arbitrary solution to a problem, then attempts to find a better solution by incrementally changing a single element of the solution. If the change produces a better solution, an incremental change is made to the new solution, repeating until no further improvements can be found [Ska94], which is illustrated in Fig 2.5.

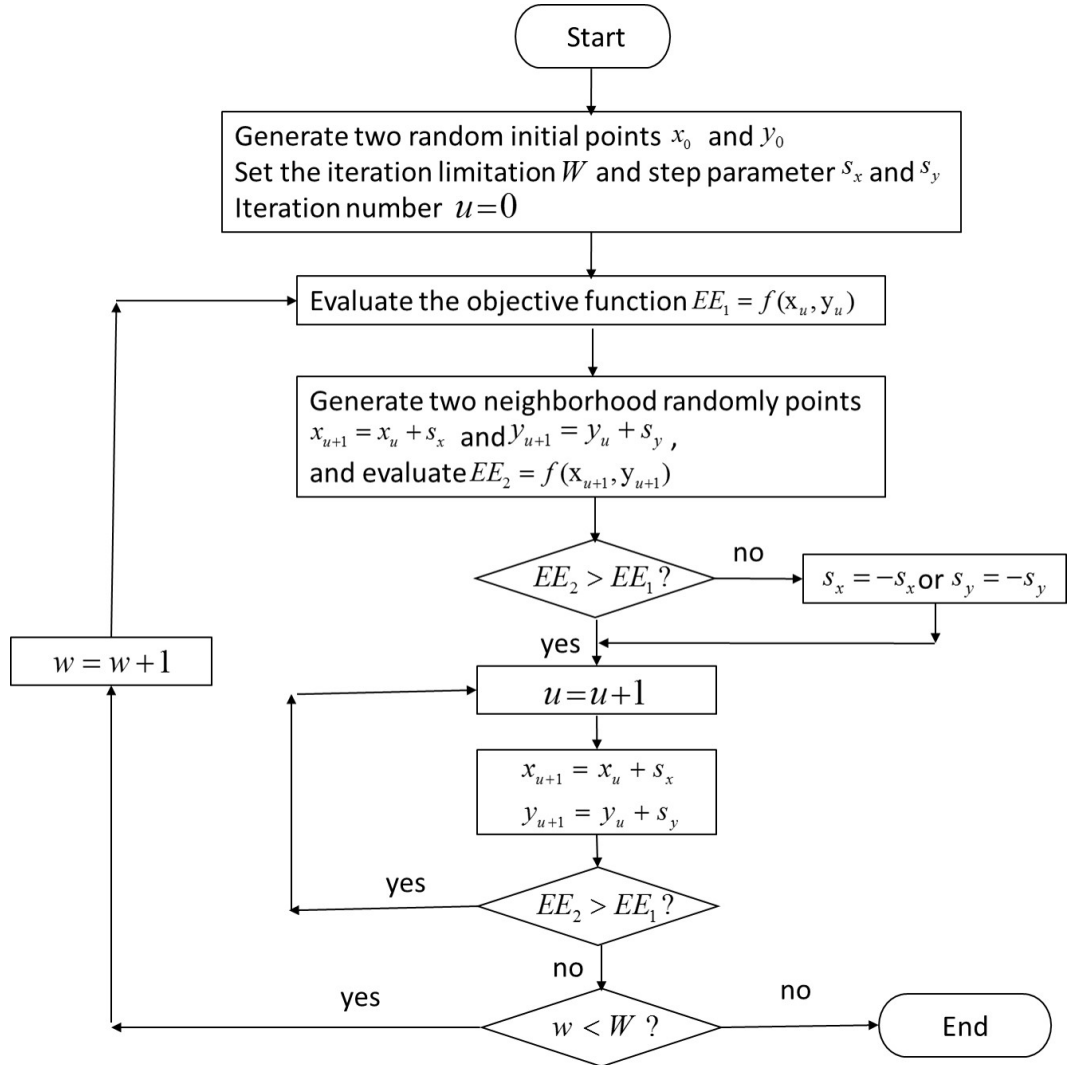


Fig. 2.5: Hill Climbing flowchart.

As Hill Climbing is simple and the optimum is obtained in convex problem, this

algorithm is applied to find upper bound of energy efficiency for RAW control.

2.2.2 Simulated Annealing

Simulated Annealing is a probabilistic technique for approximating the global optimum of a given function [Hwa88], which is a meta-heuristic to approximate global optimisation in a large search space [Dav87]. It is often used when the search space is discrete. For problems where finding an approximate global optimum is more important than finding a precise local optimum in a fixed amount of time, Simulated Annealing may be preferable to alternatives such as Gradient Descent.

The name and inspiration come from annealing in metallurgy, a technique involving heating and controlled cooling of a material to increase the size of its crystals and reduce their defects. Both are attributes of the material that depend on its thermodynamic free energy. Heating and cooling the material affects both the temperature and the thermodynamic free energy [Egl90].

Simulated Annealing interprets slow cooling as a slow decrease in the probability of accepting worse solutions as it explores the solution space [Kir84]. Accepting worse solutions is a fundamental property of meta-heuristics because it allows for a more extensive search for the optimal solution [DSE02]. Slow cooling is implemented in the Simulated Annealing algorithm as a slow decrease in the probability of accepting worse solutions as it explores the solution space [GFR94]. The procedure of the algorithm is illustrated in Fig. 2.6. It starts with a potential solution to the problem and defines a large temperature. Then a value will be added to the solution to obtain a new outcome and the gap between old and new outcomes. According to Metropolis rule, when $t < 0$, the new solution is acceptable, otherwise the probability to accept the solution is $\exp(-\frac{t}{T})$. If acceptable, the current solution will be replaced by the new solution. The loop goes on until the temperature reaches a certain value.

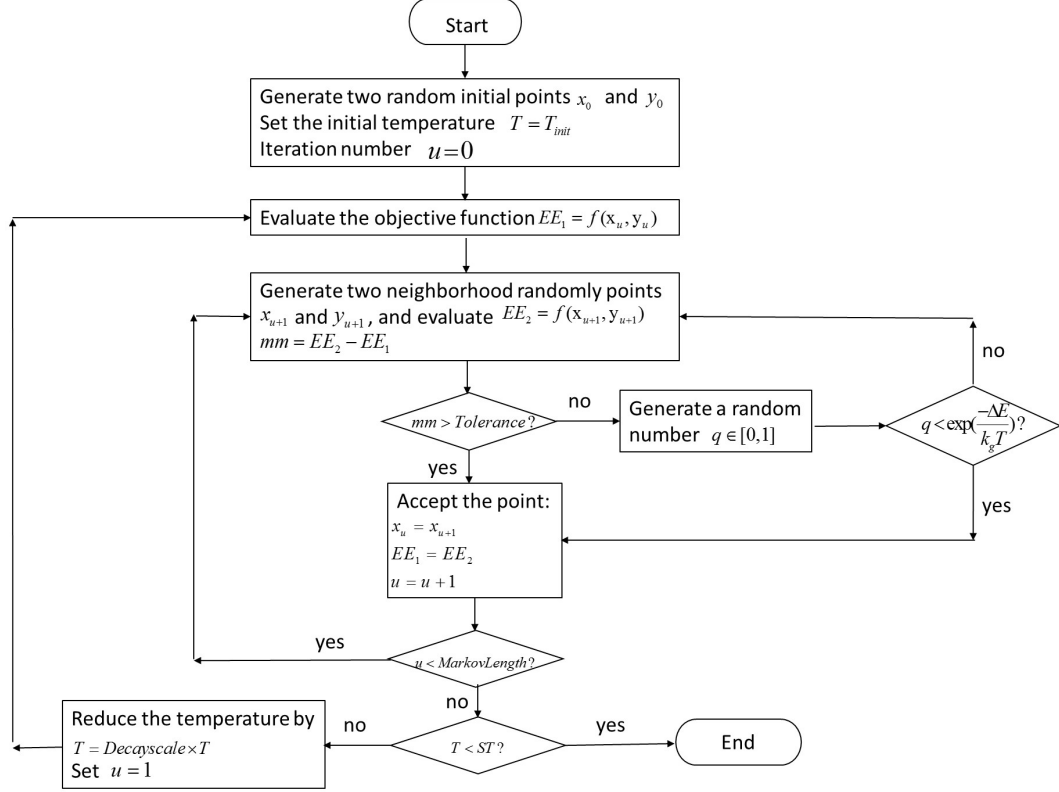


Fig. 2.6: Simulated Annealing flowchart.

As Simulated Annealing is suitable for discrete search space to find approximate optimum in limited time, this algorithm is applied to find the upper bound of energy efficiency for RAW control under a large and discrete search space.

2.2.3 Gradient Descent

Gradient Descent (also known as Steepest Descent) is a first-order iterative optimisation algorithm, which can work in spaces with any number of dimensions, even in infinite-dimensional ones [BM99]. It is a fast and cheap iteration when perturbation and evaluation are both incremental. A local minimum of a function can be obtained by Gradient Descent through taking steps proportional to the negative of the gradient (or of the approximate gradient) of the function at the current point, while a local optimum

can be found through taking steps proportional to the positive of the gradient [BSR⁺05], shown in Fig. 2.7.

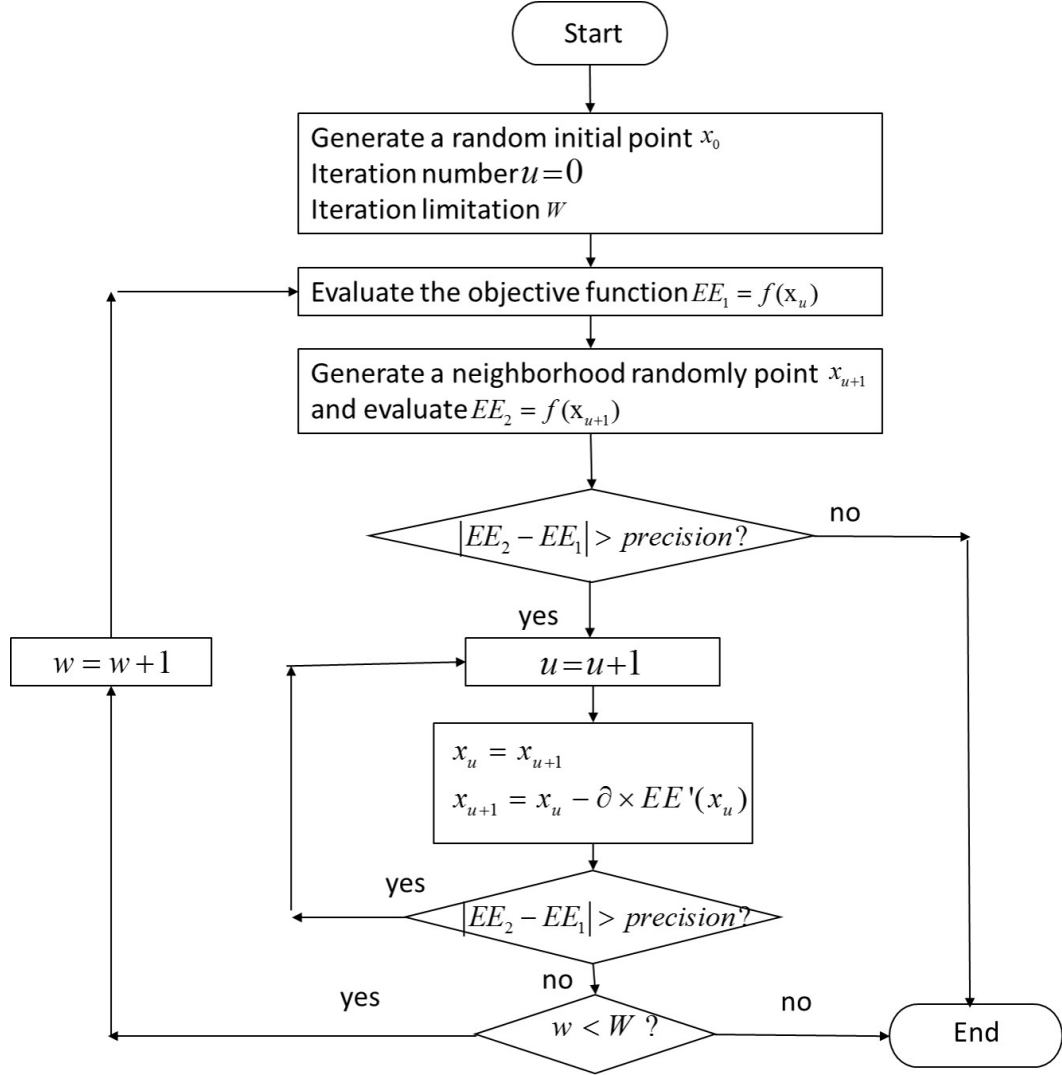


Fig. 2.7: Gradient Descent flowchart.

The Gradient Descent can take many iterations to compute a local minimum with a required accuracy, if the curvature in different directions is very different for the given function. For such functions, preconditioning, which changes the geometry of the space to shape the function level sets like concentric circles, cures the slow convergence. However, constructing and applying preconditioning can be computationally expensive [Qia99].

As Gradient Descent is a fast technique with small computing space, this algorithm is applied to find the upper bound of energy efficiency for RAW control and optimal window size for different number of devices under diverse scenarios.

2.3 State-of-the-art

2.3.1 Channel Access in IEEE 802.11ah

In IEEE 802.11ah based networks, the energy efficiency can be improved by increasing the successful transmission probability, decreasing access collision and saving access energy.

In [PHL14], a medium access control enhancement algorithm was proposed to optimise uplink transmission probability. It estimates the number of devices for the uplink access according to the successful transmission probability and then determines the optimal size of the RAW based on the relationship between the estimated number of devices and RAW size. To providing a reliable and efficient service for IEEE 802.11ah based networks, an adaptive access mechanism was presented in [MSP16] based on a periodically reoccurring pool of time slots, whose size is proactively determined on the basis of the reporting activity in the cell to supports all potential periodic, on-demand, and alarm reporting M2M reporting regimes.

To reduce the collision probability, a short-frame based RAW access approach was proposed in [ZWZL13]. In this approach, the devices first send a short frame to AP to indicate device states at the beginning of RAW in order to avoid unused slots due to the devices in doze state. In [BAB⁺14], a CAS-based channel access protocol was proposed to achieve a good trade-off between energy consumption and packet delivery ratio both in downlink and uplink RAW segments. By means of this protocol, the RAWs

designated to the devices are divided into two different segments (downlink and uplink) which, in turn, are divided into dynamic Channel Access Slots (CASs). In each CAS, a selected group of devices compete for transmitting data.

Grouping is another way to reduce the contention. To decreasing the collision probability and save access resource a virtual grouping method was proposed in [OMYS13] to mitigate degradation of the throughput and delay performance in WLANs that employ a CSMA/CA protocol. It is achieved by finding the devices in successive non-contention states and putting them in sleep mode. In [CLLC15], a load balancing grouping scheme was proposed to group the high dense devices to improve channel utilisation by considering load and traffic. [KHU⁺16] proposed a grouping strategy of the renewal access protocol based on transmission attempts to optimise the network throughput for any group structure.

To reserve the access energy, Offset ListenInterval algorithms were proposed to enhance existing power save mechanisms to extend the lifetime of a Machine-to-Machine (M2M) or smart grid communication network in [LSC13] and [LSC14]. The Offset ListenInterval algorithms spread the M2M or smart grid traffic evenly with calculated offsets to alleviate network contention and reduce packet delay. A dynamic membership change mechanism for a large-scale 802.11ah wireless sensor network was presented in [KC17] to prolong the lifetime of STAs by increasing their sleeping periods by reducing the number of devices that have to unnecessarily wake up under the 802.11ah power saving mechanism. [Arg15] explored signal estimation problem in a cooperative 802.11ah network with relays with the aim of minimising the power consumption via setting the optimal power for each device considering the location of the fusion centre and the relay.

As energy efficiency is a main criteria in IoT networks and RAW size has the a great impact on access for massive devices in IEEE 802.11ah networks, the adaptive RAW is considered in this thesis to improve energy efficiency for highly dense sensor

networks.

2.3.2 Harvested Energy Powered MAC

MAC protocols for energy harvesting sensor networks have been extensively explored in the recent past. In [GKAAZ17], an energy harvesting enabled contention-tree based access scheme was proposed to improve network performance, which resolves collisions and takes energy availability into account. Results reveal the trade-off between both performance metrics (packet delivery ratio and time efficiency) and how they are influenced by the number of slots per frame, the energy harvesting rate and the number of end-devices. [NKN16] proposed an adaptive packet transmission algorithm to optimise energy efficiency and QoS for IEEE 802.15.4 based harvested-energy powered networks by adapting the active sleeping period in response to various IoT traffic load conditions, residual energy of sensor nodes and available Radio Frequency (RF) energy from the Long Term Evolution (LTE) Evolved Node B (eNodeB). An efficient MAC protocol incorporating with p-persistent CSMA mechanism was designed for energy harvesting M2M networks in [LYY⁺15] which allows devices with different energy harvesting abilities to obtain hierarchical transmission probabilities by setting the optimal contending probabilities, duration of energy harvesting period and contending period. To solving performance degrading of changing the wake-up interval regularly in a multi-hop network, [LPBS15] presented a wake-up variation reduction power manager and synchronised wake-up interval MAC for wireless nodes powered by a periodic energy source such as light energy in an office over a constant cycle of 24 hours to reduce the latency. A polling based medium access mechanism was showed in [ETS11] for single-hop sensor networks by utilise the charge-and-spend paradigm for harvesting strategy. Conventional MAC protocols such as the classical TDMA and variants of ALOHA are evaluated assuming out-of-band RF transfer in [ISS12].

2.3.3 Prioritised MAC

There are plenty of research works which investigate the prioritised medium access scheme in various applications scenarios to enhance the network performance. In [FRVM16], an enhanced priority MAC was proposed to reduce the latency of all supported traffic categories while fulfilling the stringent requirements by letting the highest priority traffic postpone lowest priority transmissions. For visible light communications, a mechanism to support priority MAC based on multi-parameter (number of back-off times, back-off exponent and contention window) was proposed in [VHJ⁺11] for IEEE 802.15.7 to improve the throughput, and the throughput of proposed mechanism was analysed by a discrete time Markov chain. A cooperative multi-group priority based MAC protocol was stressed in [YWWL09] to exploit the cooperation diversity for throughput enhancement over multi-packet reception channels through efficiently utilizing the idle periods for packet relaying and effectively limiting the throughput loss resulting from the relay phase. For industrial wireless sensor and actuator networks, PriorityMAC was proposed in [SZBG14] as a priority-enhanced medium access control protocol to provide a service differentiation for traffic categories of different priorities to enhance access for the critical and aperiodic traffic. [CLG⁺00] investigated the ability of the 802.14 MAC protocol to provide priority access to stations and proposed a multilevel priority collision resolution scheme by separating and resolving collisions between stations in a priority order to achieve the capability for pre-emptive priorities. In hybrid fiber coaxial applications and services such as voice, video, and interactive data services.

2.4 Summary

This chapter provides the introduction of IEEE 802.11ah and current research efforts on massive channel access control. IEEE 802.11ah is a promising technique for future IoT applications for highly dense devices over a large transmission range, in which RAW is a main novel mechanism applied in MAC layer to limit collisions for massive access. In

addition, the relevant methodologies applied in this thesis are provided as Hill Climbing, Simulated Annealing and Gradient Descent. In the end, the state-of-the-art reviews on channel access in IEEE 802.11ah networks, harvested energy powered MAC and prioritised MAC with the aim of improving network performance are presented.

Chapter 3

Restricted Access Window Size Control

This chapter presents the adaptive RAW scheme framework and RAW size control to improve uplink energy efficiency of IEEE 802.11ah. Two access window algorithms are proposed within RAW size control to optimise energy efficiency as well as delay for IEEE 802.11ah. Section 3.1 presents the motivation of new RAW size control in IEEE 802.11ah. The framework of adaptive RAW scheme is proposed in Section 3.2. Additionally, the general system model, energy efficiency optimisation formulation, relationship between energy efficiency and RAW size are introduced in Section 3.3. Within Section 3.3, the optimal combination of the number of time slots in one RAW and the group size is also developed in terms of energy efficiency. Finally, in Section 3.4, two novel algorithms in the window size control for IEEE 802.11ah networks are proposed to improve energy efficiency: (1) energy-aware access window algorithm for diverse group sizes through adaptive number of time slots in related window to improve energy efficiency; (2) energy-delay aware access window algorithm to adapt the number of slots and slot duration for various group sizes and application types to realise joint optimisation of energy efficiency and delay.

3.1 Motivation

The access process in IEEE 802.11ah is limited by RAW to alleviate contention for highly dense devices. RAW size has the influence on the number of devices accessing within a period of time as well as the energy consumed in the process of access. The internal slot interval provides the sufficient time for devices contending and accessing, but unsuitable duration would enlarge the waiting time and wake-up time for devices, leading to long delay and high wake-up energy consumption.

There is no standard definition for RAW duration, which affects the energy efficiency. With long RAW duration, the devices in the group need to be in active mode for a long period, leading to expending idle wake-up energy. On the contrary, the collision probability would be high if a large number of devices access through RAW with limited time slots, resulting in low efficiency. Adaptive time slot duration can provide sufficient time for devices to access and transmit, but also avoid needless idle time. RAW has the effect on signalling energy consumption to inform scheduling information. Thus appropriate number of devices in adaptive RAW duration can reduce low energy consumption and achieve a high throughput. In the following work, the RAW size control is proposed to adapting window size (number of slots and slot interval) to optimise energy efficiency.

3.2 Adaptive RAW Scheme Framework

A two-stage adaptive RAW scheme is proposed for IEEE 802.11ah based networks, which is shown in Fig. 3.1. The first stage is RAW size control to adapt RAW size based on standard operation, which is the foundation for stage 2. For different scenarios, the network requirements vary. Hence, based on adaptive window size, the additional considerations need to be added to meet the different specifications, such as low-delay, energy availability, and priority in time-critical networks. Motivated by that, the second stage includes three controls: RAW retransmission control, harvested-energy powered

access control and priority-aware channel access control.

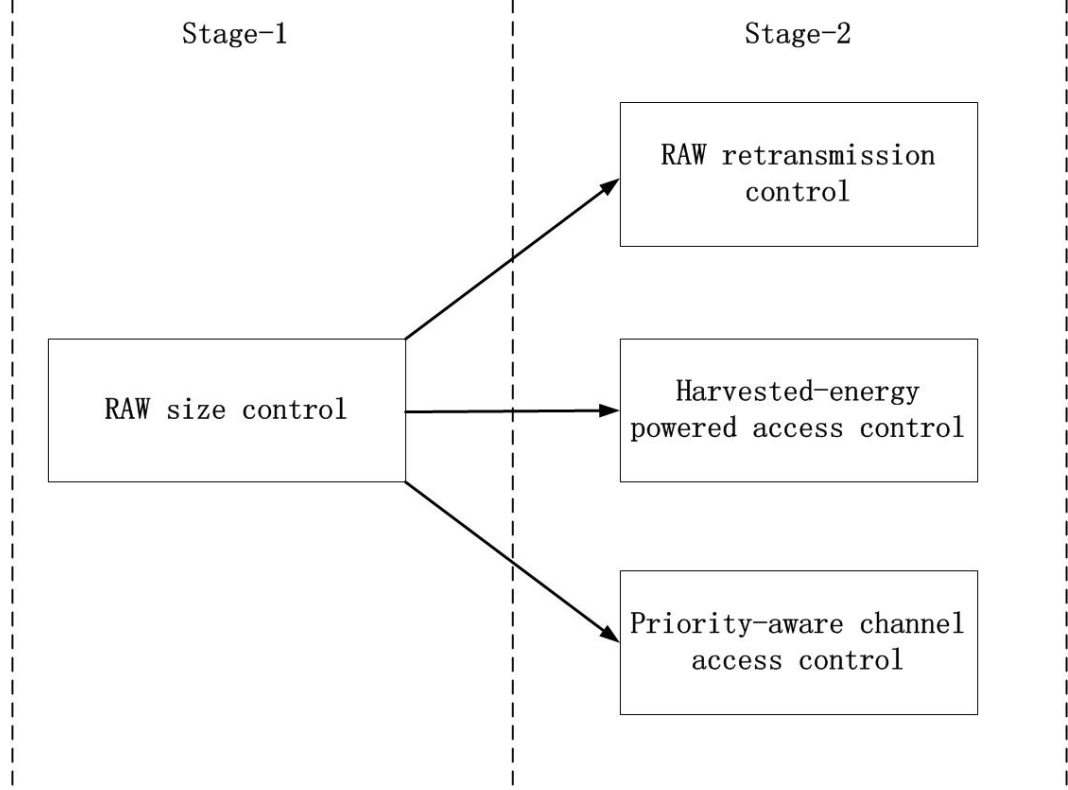


Fig. 3.1: Two-stage adaptive RAW scheme.

3.3 Problem Description

3.3.1 System Model

An IEEE 802.11ah based network as one AP with 6000 devices is considered. The devices are randomly clustered into several groups, where each group is assigned to a RAW to access channel. In IEEE 802.11ah uplink communications, for each RAW, there are M time slots and N devices limited by the lowest and highest AID of devices indicating the location, traffic, type, and energy saving mode [KLKG15]. The devices which have buffered data for the AP randomly select one of the uplink time slots in their allocated RAW and attempt to access the channel. The access process via RAW is shown in Fig. 3.2.

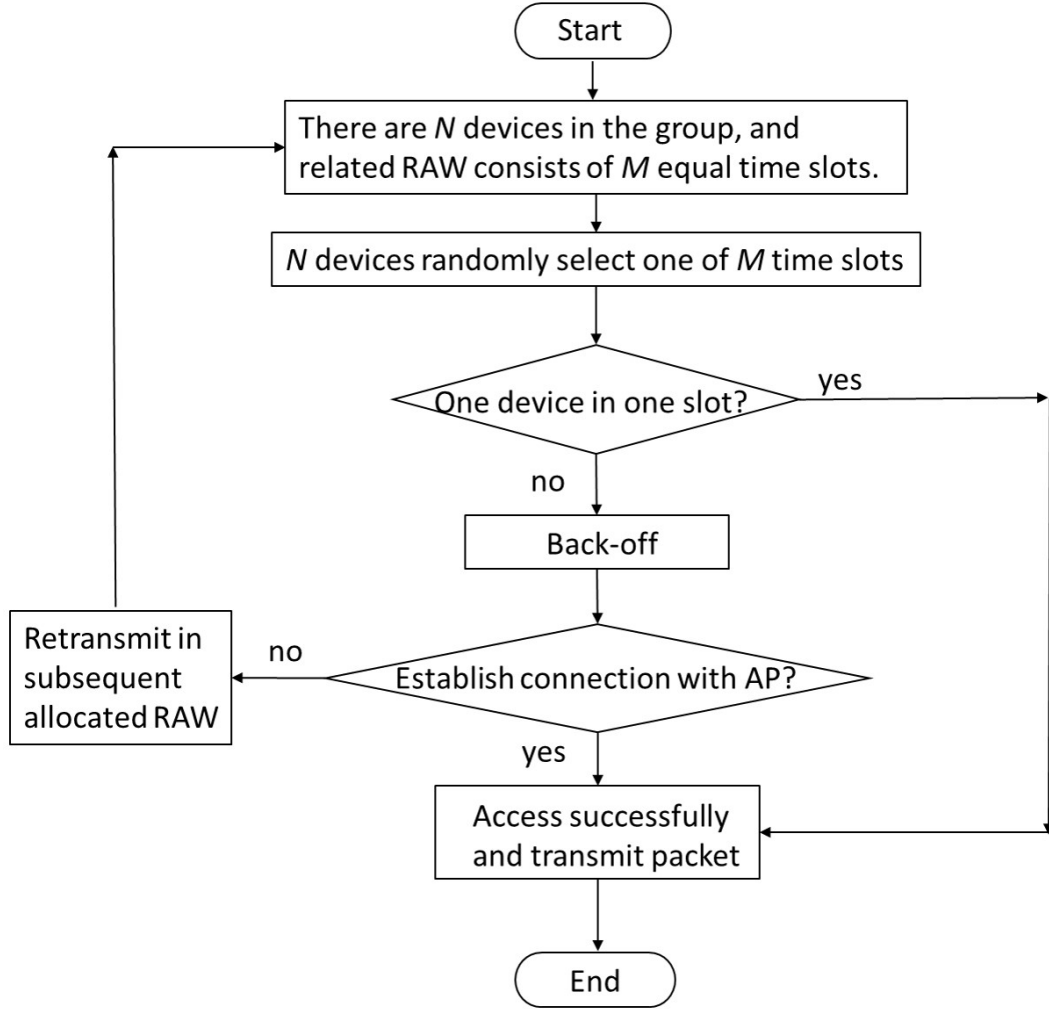


Fig. 3.2: Uplink channel access in IEEE 802.11ah.

As an example shown in Fig. 3.3, after random selection, if there is only one device choosing a slot, it can access the channel directly, for example, Device 1 transmits the packet without contention in Slot 1, and the same for Devices 3 in Slot 5, Device $N(j) - 2$ in Slot $M(j)$, and Device $N(j)$ in Slot 3. When there are more than one devices choosing the same time slot, for example, Device 2, Device 4, Device $N(j) - 4$ and Device $N(j) - 1$ in Slot 2, they would enter the back-off stage (signed as grey in Fig. 3.3) to avoid collision by doubling contention window and trying again until reaching the slot boundary. Device 2 accesses the channel successfully in the back-off stage, so Device 2 transmits uplink

data to AP, while Device 4, Device $N(j) - 4$ and Device $N(j) - 1$ need to re-transmit in the subsequent allocated window. If accessing the channel successfully, device requests uplink communications by sending a PS-poll message to the AP. The AP responds with an ACK to confirm the connection. After the first handshake, the device transmits buffered uplink data frame and waits for the ACK from the AP after a SIFS period [Par13].

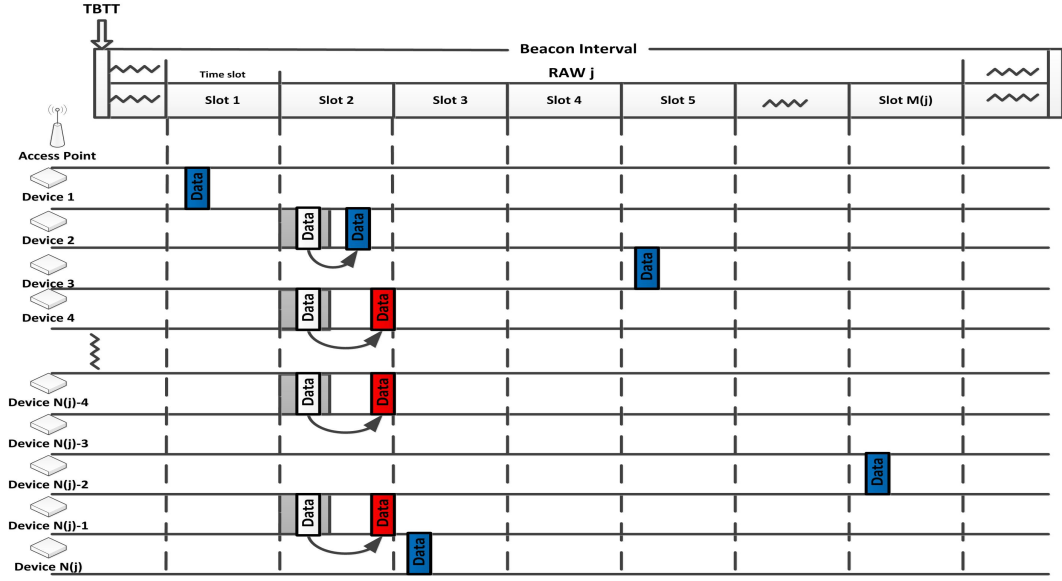


Fig. 3.3: Example of uplink RAW operation in IEEE 802.11ah.

The process is repeated, one RAW by one RAW, until the end of beacon frame as shown in Section 2.1.3 and Fig. 2.3.

3.3.2 Problem Formulation

In this section, the uplink energy efficiency optimisation problem is formulated according to the RAW based channel access mechanism. The objective function is derived by transmission probability, throughput and energy consumption, thus the computation process is divided into three steps.

1. Estimating the transmission probability for one device to access channel and transmit a single packet successfully.

2. Calculating the energy consumption (including transmission energy consumption and signalling information energy consumption) and throughput for a group of devices to attempt and transmit packets within one RAW.
3. Formulating the energy efficiency with the obtained throughput and energy consumption for one RAW.

As for uplink communications in IEEE 802.11ah, the number of devices and access period are limited by RAW, and the devices randomly select time slots in allocated RAW. According to [PHL14], there are two cases for a device to succeed in channel access. Case 1 is no contention, while Case 2 is success after contending via back-off stage.

- Case 1: the time slot is selected by only one device. Thus this device can occupy the whole slot to transmit packet directly without contention.
- Case 2: the time slot is selected by multiple devices. They would come into the back-off stage to avoid collision by doubling contention window. Subsequently, the collision does not occur if one of the devices can access the channel in the first back-off stage.

Case 1 is the state without contention as there is only one device in one slot after random selection. This device can transmit the packet directly. So the transmission probability for one device in Case 1 is that no other devices choose the slot which is selected by this device, denoted as

$$P_1 = \left(1 - \frac{1}{M}\right)^{N-1}, \quad (3.1)$$

where M is the number of time slots in one RAW, which indicates the duration of one RAW; N is the number of devices in one group that can attempt to access in one RAW.

Case 2 is the state with contention via back-off stage as when multiple devices selecting the same slot, the devices will go to back-off stage and a collision does not occur if

one of them will succeed in accessing the channel at the first back-off stage.

The probability for multiple (i and $i > 1$) devices to choose the same slot is

$$P(i) = \binom{N}{i} \left(\frac{1}{M}\right)^i \left(1 - \frac{1}{M}\right)^{N-i}. \quad (3.2)$$

So the probability of more than one device to choose the same slot is $P_{>1} = \sum_{i=2}^N P(i)$.

These i devices in one slot will go to the back-off stage. The probability for one device to build the connection with AP through minimum contention window via the first back-off stage is obtained as this device occupies the front slot without other devices, which is denoted as

$$P_{back-off}(i) = \sum_{x=0}^{W_{\min}-1} \left\{ \prod_0^x \left[1 - \frac{1}{W_{\min}} \left(1 - \frac{x}{W_{\min}} \right)^{i-1} \right] \right\} \frac{1}{W_{\min}} \left(1 - \frac{x+1}{W_{\min}} \right)^{i-1}, \quad (3.3)$$

where W_{\min} is the minimal size of contention window.

Hence, with i devices selecting the same time slot, a device can access the channel at the first back-off stage and communicate with AP with the probability of $P(i)P_{back-off}(i)$. So as i is from 2 to N , for the Case 2, the transmission probability is the sum of multiple devices in one slot as

$$P_2 = \sum_{i=2}^N P(i)P_{back-off}(i). \quad (3.4)$$

Thus, the overall transmission probability for one device to transmit one packet with a RAW is the sum of two cases, which is denoted by

$$P = P_1 + P_2. \quad (3.5)$$

The energy consumption for a device to access channel and transmit a packet in one RAW is estimated based on different states that a device may fall into with various probability, which is denoted by

$$E_t = P_1 E_{t1} + P_2 E_{t2} + (1 - P) E_c + M \tau E_{wake_up}, \quad (3.6)$$

where E_{t1} is the energy consumption when transmitting a packet successfully as Case 1; E_{t2} is the amount of energy consumed if transmitting successfully in Case 2; E_c is the energy waste when there is collision so that it needs to retransmit in subsequent allocated RAW; E_{wake_up} is the wake-up energy in one slot, which is energy consumed for idle listening; τ is the time duration of one time slot.

The size of RAW also has the impact on the energy consumption of transmitting signalling information, because for a short RAW duration, the signalling information of AP to each device will be high due to the scheduling information that needs to be transmitted multiple times in a short time. In addition, if the group size is small, it also needs massive scheduling information to realise network communications. So the energy consumption of signalling information is related to N and M :

$$E_{signal} = \frac{\alpha}{M} \times \frac{\beta}{N}, \quad (3.7)$$

where α is the parameter indicating traffic and β is the parameter related to overall number of devices in the scenario.

The overall energy consumption for a group of devices to access within one RAW consists of transmission energy and signalling energy, which is denoted by

$$E_{overall} = N(E_t + E_{signal}). \quad (3.8)$$

Throughput for a RAW is the ratio of number of bits that can be transmitted in one RAW to the RAW duration, which is formulated as

$$R = \frac{N \times P \times \gamma}{\tau M}, \quad (3.9)$$

where γ is the packet size. $N \times P \times \gamma$ is the total length of packets that can be transmitted for N devices in M time slots. τM is the total time of one RAW.

Energy efficiency for one RAW is evaluated by the throughput it provides and the overall energy consumption including transmitting energy and signalling energy.

Thus energy efficiency is

$$EE(M, N) = \frac{R}{E_{\text{overall}}} = \frac{\gamma P}{\tau M(E_t + E_{\text{signal}})}. \quad (3.10)$$

With P , E_t and E_{signal} being built by M and N , energy efficiency is a function related to the number of devices per group and time slots in one RAW. Thus, the energy efficiency can be maximised by finding the optimal M and N .

3.3.3 Relationship between Energy Efficiency and RAW

The main part of energy efficiency $f(M, N)$ is formulated on Matlab along with the various number of devices in one group (N) and the number of time slots in one RAW (M), denoted by

$$f(M, N) = \frac{P}{M(E_t + E_{\text{signal}})}. \quad (3.11)$$

Fig. 3.4 shows the numeric result of Equation 3.11. It can be observed that $f(M, N)$

is a concave surface with peak, where network would perform better with the same energy consumption. Due to the collision probability being relative high with small M and large N , the optimum should be chosen near the centre of Fig. 3.4.

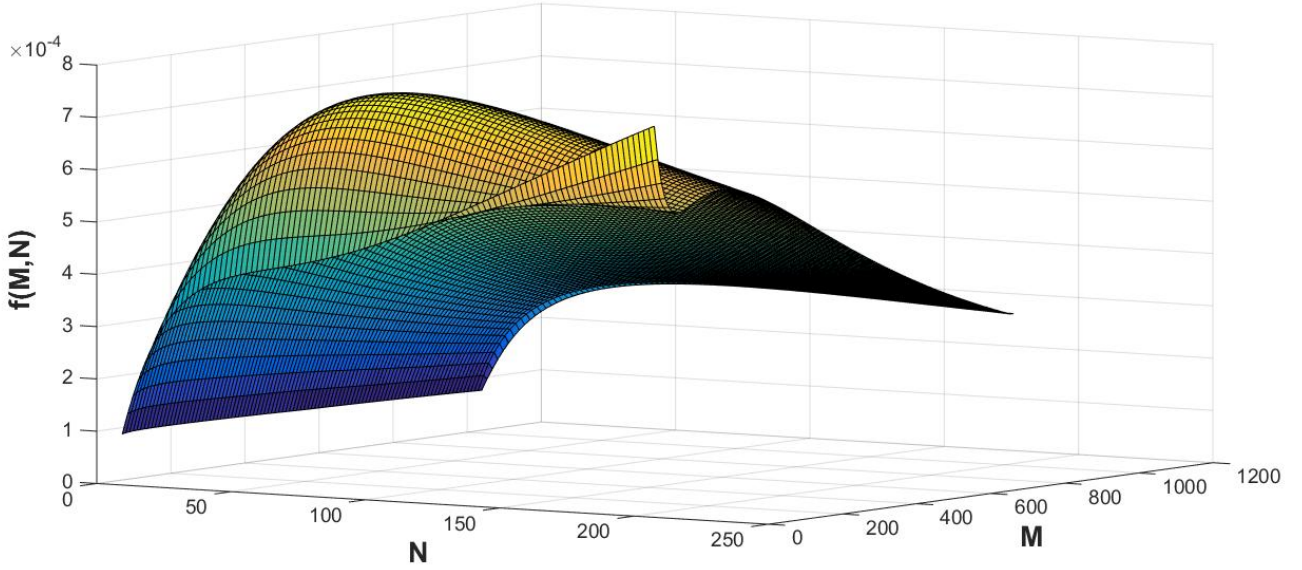


Fig. 3.4: Main part of energy efficiency, $f(M, N)$.

The optimal set of group size and RAW duration is obtained to maximise energy efficiency by applying Hill Climbing, an iterative algorithm as shown in Algorithm 1, Simulated Annealing, a probabilistic algorithm as shown in Algorithm 2, and Gradient Descent, a first-order iterative optimisation algorithm as shown in Algorithm 3.

Algorithm 1 is a standard Hill Climbing approach to find the optimal solution. It begins with a set of arbitrary values based on the generated random numbers (M and N), and then tries to find a better energy efficiency by comparing the new energy efficiency result of incremental M and N with the existing optimum. If the fresh one produces larger energy efficiency, update the optimum. Repeat the steps until climbing to the maximal energy efficiency.

Algorithm 1 Hill Climbing Access Window Algorithm

```

1: Step 1: Find optimal RAW size ( $M$ ) and group size ( $N$ ).
2: loop
3:   Step 1.1: Generate a random set ( $M, N$ ).
4:   Step 1.2: Search peak point.
5:   loop
6:      $u = 1$ ;
7:      $EE = EE(M_0, N_0)$ ;
8:     while  $u < \text{iteration}$  do
9:        $\text{new\_set} = \text{a new random set } (M_k, N_k)$ ;
10:       $\text{new\_EE} = EE(M_k, N_k)$ ;
11:      if  $u == 1$  then
12:         $\text{best\_set\_temp} = \text{new\_set}$ ;
13:      else
14:         $\text{best\_EE\_temp} = EE(\text{best\_set\_temp})$ ;
15:        if  $\text{new\_EE} > \text{best\_EE}$  then
16:           $\text{best\_set\_temp} = \text{new\_set}$ ;
17:        end if
18:      end if
19:       $u = u + 1$ ;
20:    end while
21:    if  $EE > \text{best\_EE\_temp}$  then
22:       $\text{set} = \text{best\_set\_temp}$ ;
23:    else
24:      go back to loop;
25:    end if
26:  end loop
27:   $EE = EE(M, N)$ ;
28:  if  $EE > \text{bestEE}$  then
29:     $\text{bestEE} = EE$ ;
30:     $\text{best\_set} = \text{random set } (M, N)$ ;
31:  end if
32: end loop
33: return  $\text{best\_set}$ ;
34: Step 2: AP sets the window size as  $M$  equal time slots for a group with  $N$  devices. The devices in this group fall into sleep mode and wake up until coming to their allocated window.
35: Step 3:  $N$  devices in the group try to establish connection with AP by randomly selecting one of  $M$  time slots in RAW and attempt to access the channel.
36:  $N$  devices in the group choose one of  $M$  slots randomly.
37: Devices attempt to access channel to establish connection with AP as Case 1 and Case 2. When only one device in one slot, the device accesses channel directly without contention; when multiple devices in one slot, the device go to the back-off stage to access medium.
38: When the device could not access in its slot, re-attempt in the next allocated window.

```

Algorithm 2 Simulated Annealing Access Window Algorithm

```

1: Step 1: Find optimal RAW size ( $M$ ) and group size ( $N$ ).
2: Step 1.1: Initialise random input set ( $M_0, N_0$ ) as pre_best_set and another
   random set ( $M_1, N_1$ ) as best_set.
3: Step 1.2: Search optimal point.
4: cooling until meet the requirement for iteration
5:  $mm = \text{abs}(\text{EE}(M_1, N_1) - \text{EE}(M_0, N_0));$ 
6: while  $mm > \text{Tolerance}$  do
7:    $\text{Temperature} = \text{DecayScale} \times \text{Temperature};$ 
8:   for  $u$  in the range of 0 to MarkovLength do
9:     while do
10:       $\text{next\_set} = \text{pre\_set} + \text{Step};$ 
11:      if  $\text{next\_set}$  lies out of input limitation then
12:        end the loop
13:      end if
14:    end while
15:    check whether is global optimum
16:    if  $\text{new\_EE} > \text{best\_EE}$  then
17:      reserve previous optimum
18:    end if
19:    Metropolis process
20:    if  $\text{pre\_EE} < \text{next\_EE}$  then
21:      accept this point and start next iteration based on this point;
22:    else
23:       $\text{changer} = (\text{next\_EE} - \text{pre\_EE}) / \text{Temperature};$ 
24:      if  $\exp(\text{changer}) > \text{rand}$ , do not accept new solution.
25:    end if
26:  end for
27:   $mm = \text{abs}(\text{EE}(\text{best\_set}) - \text{EE}(\text{pre\_best\_set}));$ 
28: end while
29: return best_set;
30: Step 2: AP sets the window size as  $M$  equal time slots for a group with
    $N$  devices. The devices in this group fall into sleep mode and wake up
   until coming to their allocated window.
31: Step 3:  $N$  devices in the group try to establish connection with AP by
   randomly selecting one of  $M$  time slots in RAW and attempt to access
   the channel.
32:  $N$  devices in the group choose one of  $M$  slots randomly.
33: Devices attempt to access channel to establish connection with AP as Case 1 and
   Case 2. When only one device in one slot, the device accesses channel directly
   without contention; when multiple devices in one slot, the device go to the back-off
   stage to access medium.
34: When the device could not access in its slot, re-attempt in the next allocated window.

```

Algorithm 2 is a standard Simulated Annealing approach to find the optimal energy efficiency. The search begins with a random set (M and N), and then compares the existing energy efficiency with a new result with input that adding a step. When upcoming one performs better, accept new energy efficiency, otherwise, reserve the previous. If the gap is larger than tolerance, cool one time and decrease temperature until annealing. The times loop will go according to Markov length.

Algorithm 3 Gradient Descent Access Window Algorithm

- 1: **Step 1: Find optimal RAW size (M) and group size (N).**
 - 2: **loop**
 - 3: Initialise (M_0, N_0) and (M_1, N_1) as two random numbers.
 - 4: $EE'(M) = \frac{\partial(-EE(M, N))}{\partial M}$
 - 5: $EE'(N) = \frac{\partial(-EE(M, N))}{\partial N}$
 - 6: **while** $|EE(M_{old}, N_{old}) - EE(M_{new}, N_{new})| \geq precision$ **do**
 - 7: $\partial = 0.01$
 - 8: $M_{old} = M_{new}$
 - 9: $N_{old} = N_{new}$
 - 10: $M_{new} = M_{old} - \partial \times EE'(M)$
 - 11: $N_{new} = N_{old} - \partial \times EE'(N)$
 - 12: **end while**
 - 13: return M and N
 - 14: $best_set = (M, N)$
 - 15: **end loop**
 - 16: **Step 2: AP sets the window size as M equal time slots for a group with N devices. The devices in this group fall into sleep mode and wake up until coming to their allocated window.**
 - 17: **Step 3: N devices in the group try to establish connection with AP by randomly selecting one of M time slots in RAW and attempt to access the channel.**
 - 18: N devices in the group choose one of M slots randomly.
 - 19: Devices attempt to access channel to establish connection with AP as Case 1 and Case 2. When only one device in one slot, the device accesses channel directly without contention; when multiple devices in one slot, the device go to the back-off stage to access medium.
 - 20: When the device could not access in its slot, re-attempt in the next allocated window.
-

Algorithm 3 is a standard Gradient Descent approach to find the optimal energy efficiency. Same as Algorithm 1 and Algorithm 2, it starts with an arbitrary value (M , N). Subsequently, it compares the existing energy efficiency with a new result with the

updated input that adding a gradient value. If upcoming one is higher, accept new one, otherwise, reserve previous. Step by step to find the optimal value according to gradient descent route.

3.3.4 Simulation Results

In this section, the result of optimisation algorithms for RAW is evaluated in Matlab. An IEEE 802.11ah network is considered as described in the system model. Each involved device has exactly one uplink packet to transmit in one RAW. The optimal value is found based on the setting of 200 to α and β respectively. The main simulation parameters are given in Table 3-A.

Table 3-A: Simulation Parameters for Upper Bound Energy Efficiency in IEEE 802.11ah Uplink Communications

Parameter	Value	Parameter	Value
Frequency	0.9 GHz	Data rate	100 kbps
Case 1 transmit power	1.346 mw	Case 2 transmit power	2.5 mw
Collision power	3.0 mw	Idle listening power	0.001 mw
Slot duration	31.1 ms	Packet length	1024 bits
Min contention window	8	Max contention window	1024

Fig. 3.5 shows the energy efficiency with three different RAW sizes ($M=90, 180, 270$) varies over diverse group sizes. It can be seen the curves are concave and the optimal duration ($M=180$) leads to better performance when comparing with $M=90$ and $M=270$. The peak point is at 90 with $M=180$, which fits the theory analysis result, and is 9% higher than the peak at $M=90$ or 270.

As for the behaviour with optimal RAW size ($M=180$), the curve keeps sharp growth with increasing number of devices before M reaching 90. The optimum improves 20% compared with 50 devices. In addition, after the peak, the trend is down. Energy effi-

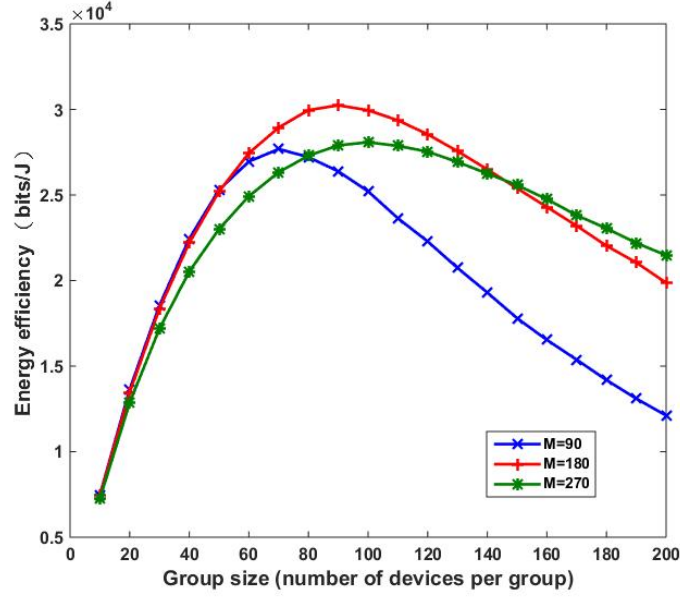


Fig. 3.5: Energy efficiency per RAW with different group sizes for three window sizes ($M=90, 180, 270$).

ciency decreases to around 10% if the number of devices reduces from 130 to 90.

With the small number of devices in one group, energy efficiency of three scenarios have the similar performance due to the fact that the ratio of time slots to devices is high, resulting in few collisions. However, there are small number of devices or packets transmitting in one RAW, thus signalling energy dominates the energy consumption. With the rising number of devices, in terms of the whole networks, signalling informations do not need to be sent multiple times. It increases 42.8% for 30 devices per group compared with 20. However, after the peak, the trend declines. In addition, the rate of decline is higher when duration is shorter. With the increasing of group sizes, the collision probability will be high which leads to more consumed energy and low throughput, which are the two parameters for low efficiency, where it is also the reason that the scenario with fewer time slots for devices performs worse.

Fig. 3.6 shows the energy efficiency with three group sizes ($N=45, 90, 135$) as it varies along diverse number of time slots in one RAW. The highest point is at $M=180$,

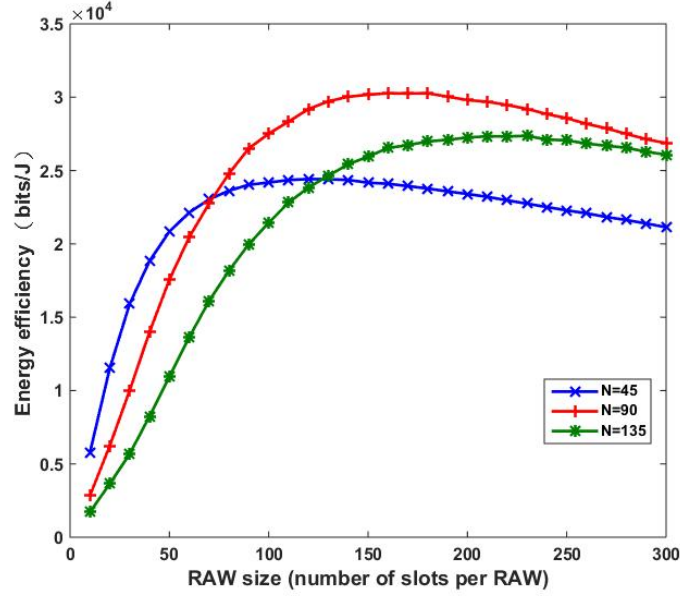


Fig. 3.6: Energy efficiency per RAW with different RAW sizes for three group sizes ($N=45, 90, 135$).

$N=90$ abiding with the theoretical analysis. It is obvious that the optimal group size ($N=90$) has better energy efficiency, approximately 11% higher for peak point in $N=90$ comparing with the peak of the other two scenarios.

For $N=90$, the optimal number of devices is 70% better than 50 slots per RAW, and 9% better than 300 slots per RAW. Although the peak is at $M=180$, the curve is nearly stable around the peak. Hence, choosing proper group size and RAW duration leads to improvement in energy efficiency.

When the RAW duration is short, the three curves all go up, where the gradients are negatively correlated with the number of devices. At this stage, collision dominates the throughput and energy consumption. So with increasing duration, there are more choices for devices, thus fewer collision which improves the energy efficiency. That also is the reason that lowest number of devices has higher efficiency. However, if the RAW duration is too large, due to long time to be wake-up mode, idle listening energy of devices will be high which makes energy efficiency drop. As for $N=45$, signalling infor-

mation energy is consumed much more than the other two, so it is the worst one when duration is large.

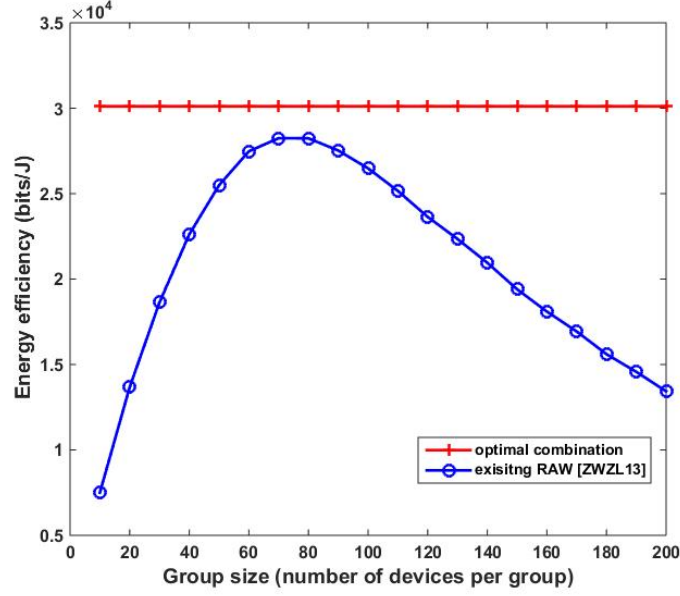


Fig. 3.7: Energy efficiency comparison between upper bound and existing RAW in [ZWZL13].

Fig. 3.7 shows the comparison between existing RAW and the proposed one. The compared existing RAW in [ZWZL13] selected 100 time slots per RAW. According to Fig. 3.7, the energy efficiency of existing RAW has a similar trend with the curves in Fig. 3.5 versus different number of devices. However, the maximum energy efficiency which the existing RAW could achieve is still lower than our proposed RAW set ($N=90$, $M=180$). The minimum energy efficiency improvement of the proposed RAW is approximate 6% compared to the existing RAW.

So simulation results demonstrate the energy efficient RAW that the combination of the number of devices per group and RAW duration can bring about superior energy efficiency for IEEE 802.11ah uplink communications.

3.4 RAW Size Control

This section presents a RAW size control for AP to set the adaptive window size based on the diverse groups. Two access window algorithms are proposed to improve energy efficiency: the first one called energy-aware access window algorithm to optimise energy efficiency via adaptive number of slots per RAW, the second one called energy-aware access window algorithm to jointly optimise energy efficiency and delay via adaptive number of slots and slot duration per RAW.

3.4.1 Energy-aware Access Window Algorithm with Fixed RAW Slot Interval

In this section, an energy-aware access window algorithm is proposed to optimise energy efficiency through adaptive RAW duration based on the number of devices per group.

The main part of energy efficiency $f(M)$ is denoted by

$$f(M) = \frac{P}{M[E_t + E_{signal}]} \quad (3.12)$$

Due to P_1 and P_2 could be regarded as binomial distribution, if N is large (i.e., $N \geq 20$), the expression can be approximated by the Poisson distribution:

$$P_1 = Ne^{-\frac{N}{M}}, \quad (3.13)$$

$$P_2 = \sum_2^N P_{back_off}(i) \frac{(\frac{N}{M})^i e^{-\frac{N}{M}}}{i!}. \quad (3.14)$$

So the $f(M)$ can be expressed as

$$f(M) = \frac{Ne^{-\frac{N}{M}}}{(M)^2 \tau E_{wake_up} + MN(E_{t1} - E_c)e^{-\frac{N}{M}} + ME_c}. \quad (3.15)$$

The second order derivation is the main factor to show the function's concavity and convexity. Through operation, the result of the second order derivation can be simplified as

$$f''(M) = \frac{e^{\frac{-N}{M}} N^2 \ln e(N \ln e - 2M)}{M^4 [E_c M + (E_{t1} - E_c) M N e^{\frac{-N}{M}} + \tau E_{wake_up}(M)^2]}, \quad (3.16)$$

which is negative due to $N \ln e - 2M < 0$ and $E_c M + (E_{t1} - E_c) M N e^{\frac{-N}{M}} > 0$, indicating it is a concave curve along different RAW durations with one peak point.

The optimal RAW size is found for different number of devices per group to maximise energy efficiency by applying Gradient Descent as shown in Algorithm 4.

Algorithm 4 Gradient Descent Energy-aware Access Window Algorithm

- 1: **Step 1: AP identifies the number of devices per group N .**
 - 2: **Step 2: Estimate the optimal uplink RAW size for a certain group.**
 - 3: **loop**
 - 4: Initialise M_{old} and M_{new} as two random numbers.
 - 5: $EE'(M) = \frac{\partial(-EE(M,N))}{\partial M}$
 - 6: **while** $|EE(M_{old}) - EE(M_{new})| \geq precision$ **do**
 - 7: $\partial = 0.01$
 - 8: $M_{old} = M_{new}$
 - 9: $M_{new} = M_{old} - \partial \times EE'(M)$
 - 10: **end while**
 - 11: return M
 - 12: **end loop**
 - 13: **Step 3: AP sets the window size as M equal time slots. The devices in this group fall into sleep mode and wake up until coming to their allocated window.**
 - 14: **Step 5: N devices in the group try to establish connection with AP by randomly selecting one of M time slots in RAW and attempt to access the channel.**
 - 15: N devices in the group choose one of M slots randomly.
 - 16: Devices attempt to access channel to establish connection with AP as Case 1 and Case 2. When only one device in one slot, the device accesses channel directly without contention; when multiple devices in one slot, the device contend and attempt to access medium via the back-off stage.
 - 17: When the device can not access in its slot, re-attempt in the next allocated window.
-

Algorithm 4 is a Gradient Descent approach to find the optimal window size for a group, which is a method with less working and storage space. It begins with initial

RAW sizes and finds the optimal RAW size according to the gradient descent route.

3.4.2 Simulation Results

In this section, the optimised energy-aware access window algorithm is evaluated in Matlab. An IEEE 802.11ah network as a AP with 6000 devices is considered as described in the system model. Every device has exactly one packet for uplink communications during a RAW. The optimal value is found based on the setting of 200 to α and β respectively. The main simulation parameters are given in Table 3-B, which is the same as the one applied in exploring the upper bound energy efficiency.

Table 3-B: Simulation Parameters for Energy-aware Access Window in IEEE 802.11ah Uplink Communications with Fixed RAW Slot Interval

Parameter	Value	Parameter	Value
Frequency	0.9 GHz	Data rate	100 kbps
Case 1 transmit power	1.346 mw	Case 2 transmit power	2.5 mw
Collision power	3.0 mw	Idle listening power	0.001 mw
Slot duration	31.1 ms	Packet length	1024 bits
Min contention window	8	Max contention window	1024

Fig. 3.8 shows the energy efficiency varying over diverse group sizes. The number of time slots in existing RAW is fixed [ZWZL13], while the proposed one sets the RAW size based on the group scales. For energy efficiency, the proposed RAW outperforms the existing one with the improvement of 20% in general. The peak point of existing RAW is at $N=70$, while that of the proposed RAW is at $N=90$ and 7% higher. When the number of devices is low, the trends of energy efficiency for both two RAW mechanism go up since with an increase in the number of devices, the signalling information does not need to be sent multiple times to realise communications for the whole network, which lowers the energy consumption in informing scheduling. After the peak, more devices per group would lead to high collision probability, which results in low energy efficiency,

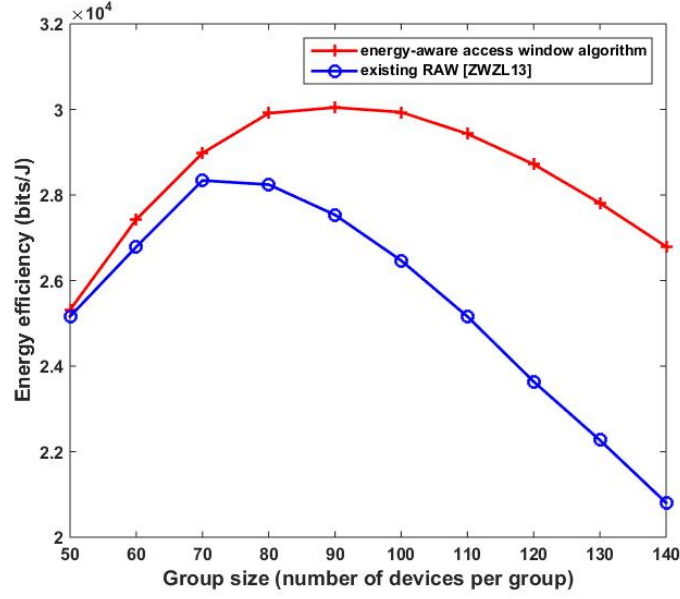


Fig. 3.8: Energy efficiency comparison per RAW with different group sizes between energy-aware access window and existing window in [ZWZL13].

so the trends decline. The proposed RAW could set the RAW dynamically based on different scenarios, thus more time slots would be set in one RAW for larger group scale, bringing in higher energy efficiency.

Fig. 3.9 shows the delivery ratio varying over diverse group sizes. As for uplink packet delivery ratio in one RAW, the proposed one improves in general 50% when comparing with the existing RAW in [ZWZL13]. With the rising number of devices per group, the trends of two curves go down due to higher collision probability which leads to consume more energy and less data that is successfully transmitted. The number of time slots in proposed RAW will be added for more devices involved to reduce contention, while the size of existing one is fixed no matter how many devices in each group, so the rate of decrement in proposed algorithm is lower than the existing work and the improvement is larger for higher density of devices per group.

The simulation results demonstrate the proposed energy-aware access window algo-

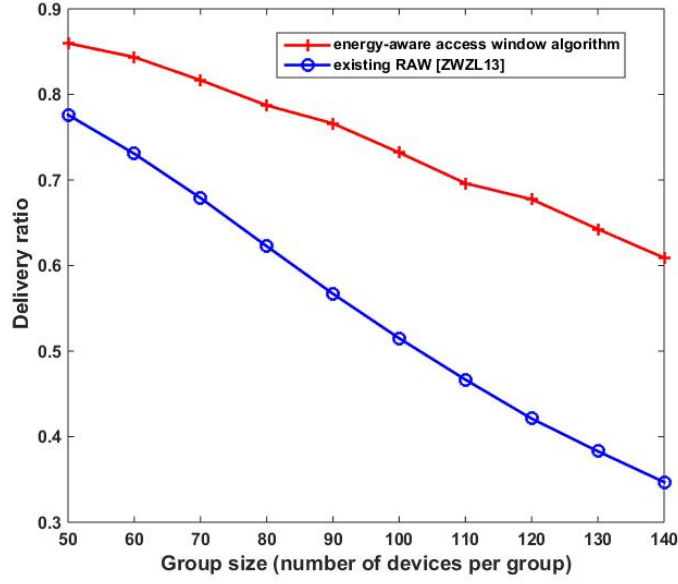


Fig. 3.9: Packet delivery ratio comparison per RAW with different group sizes between energy-aware access window and existing window in [ZWZL13].

rithm has the superior performance on uplink energy efficiency and delivery ratio than the existing control.

3.4.3 Energy-delay Aware Access Window Algorithm with Dynamic RAW Slot Interval

In this section, an energy-delay aware access window algorithm is proposed to jointly optimise energy efficiency and delay for uplink IEEE 802.11ah communications based on the formulation.

The main part $f(M)$ of uplink energy efficiency along with the various number of time slots in one uplink RAW (M) is denoted by

$$f(M) = \frac{P}{M\tau[E_t + E_{signal}]} \quad (3.17)$$

Since P_1 and P_2 can be regarded as binomial distribution, when N is large (i.e., $N \geq 20$), the expressions for the probability of both cases can be approximated by the Poisson distribution:

$$P_1 = Ne^{-\frac{N}{M}}, \quad (3.18)$$

$$P_2 = \sum_2^N P_{back-off}(i) \frac{\left(\frac{N}{M}\right)^i e^{-\frac{N}{M}}}{i!}. \quad (3.19)$$

So based on the Poisson distribution, the $f(M)$ can be expressed as

$$f(M) = \frac{Ne^{-\frac{N}{M}}}{\tau[(M)^2\tau E_{wake-up} + MN(E_{t1} - E_c)e^{-\frac{N}{M}} + ME_c]}. \quad (3.20)$$

One of the main factors to show concavity and convexity of a function is the second order derivation. Through calculation, the result of second order derivation of $f(M)$ can be simplified as

$$f''(M) = \frac{e^{-\frac{N}{M}} N^2 \ln e(N \ln e - 2M)}{\tau M^4 [E_c M + (E_{t1} - E_c) N M e^{-\frac{N}{M}} + \tau E_{wake-up} (M)^2]}, \quad (3.21)$$

which is negative as $(N \ln e - 2M) < 0$ and $E_c M + (E_{t1} - E_c) N M e^{-\frac{N}{M}} > 0$, indicating it is a concave curve with one maximum point along different uplink RAW duration.

The packet length is different for diverse type of applications. In order to guarantee the transmission, the time slots should be valid for a type of devices to access and transmit packet. Different packet sizes relate to adaptive time slots respectively, whose limitation can be described as

$$\tau \geq \frac{\gamma}{v} + \tau_{back-off}, \quad (3.22)$$

where v is the transmission rate of IEEE 802.11ah and $\tau_{back-off}$ is the back-off time when more than one device choose the same time slot.

The optimal number of slots and slot internal duration are obtained for different number of devices per group and application types to maximise energy efficiency by applying Gradient Descent as shown in Algorithm 5.

Algorithm 5 Gradient Descent Energy-delay Aware Access Window Algorithm

- 1: **Step 1: AP detects the device types (γ) and the number of devices in the group (N).**
 - 2: **Step 2: Set the constraints of optimisation. The uplink time slot durations need to be valid for a type of devices in one group to access and transmit.**
 - 3: uplink time slot duration \geq transmission time + time period for contention in back_off stage as $\tau \geq \frac{\gamma}{v} + \tau_{back_off}$;
 - 4: **Step 3: The uplink window size is determined according to the number of uplink devices in the group.**
 - 5: **loop**
 - 6: Initialise M_{old} and M_{new} as two random numbers.
 - 7: $EE'(M) = \frac{\partial(-EE(M, N, \tau))}{\partial M}$
 - 8: **while** $|EE(M_{old}, \tau) - EE(M_{new}, \tau)| \geq precision$ **do**
 - 9: $\partial = 0.01$
 - 10: $M_{old} = M_{new}$
 - 11: $M_{new} = M_{old} - \partial \times EE'(M)$
 - 12: **end while**
 - 13: return M and τ
 - 14: **end loop**
 - 15: **Step 4: AP sets the window size as M equal time slots, where the duration of each time slot is τ . The devices in this group fall into sleep mode and wake up until coming to their allocated window.**
 - 16: **Step 5: N devices in the group try to establish connection with AP by randomly selecting one of M time slots in RAW and attempt to access the channel.**
 - 17: N devices in the group choose one of M slots randomly.
 - 18: Devices attempt to access channel to establish connection with AP as Case 1 and Case 2. When only one device in one slot, the device accesses channel directly without contention; when multiple devices in one slot, the device contend and attempt to access medium via the back-off stage.
 - 19: When the device can not access in its slot, re-attempt in the next allocated window.
-

Algorithm 5 is a standard Gradient Descent approach to find the optimal solution. An arbitrary value (M) is the first potential solution of the problem. And then a addition gradient value is added to the input. If the updated EE is higher than the current EE , the new solution replaces the current solution. The loop goes on until reaching the optimal value.

3.4.4 Simulation Results

In this section, the energy-delay aware access window algorithm is evaluated in Matlab. A highly dense IEEE 802.11ah network is considered which involves 6000 devices as explained in the system model, and the novel access window algorithm is applied to the AP. Each participated device has exactly one packet to transmit for uplink communications during a RAW. The optimal value is found based on the setting of 200 to α and β respectively. The main simulation parameters are given in Table 3-C.

Table 3-C: Simulation Parameters for Energy-delay Aware Access Window in IEEE 802.11ah Uplink Communications with Dynamic RAW Slot Interval

Parameter	Value	Parameter	Value
Frequency	0.9 GHz	Data rate	100 kbps
Case 1 transmit power	1.346 mw	Case 2 transmit power	2.5 mw
Collision power	3.0 mw	Back-off time slot duration	9 μ s
Min contention window	8	Max contention window	1024

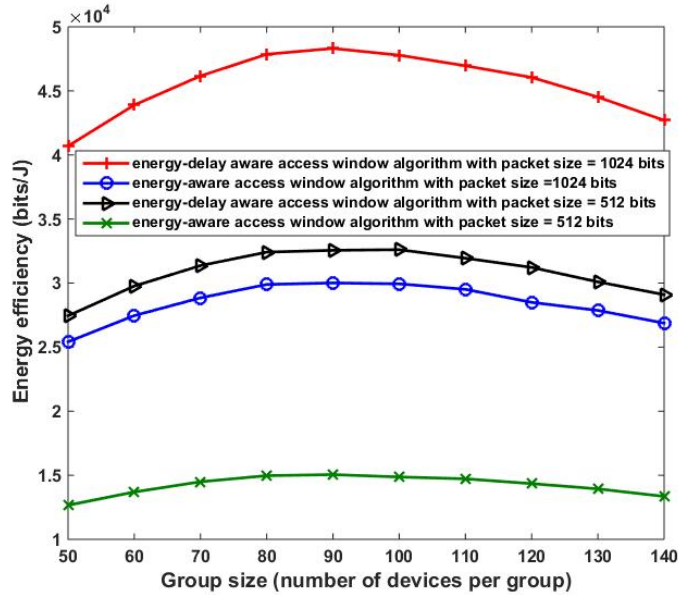


Fig. 3.10: Energy efficiency comparison per RAW with different group sizes between energy-delay aware access window and energy-aware access window.

Fig. 3.10 shows the energy efficiency for one RAW varying over diverse group sizes based on two different packet sizes (512 bits and 1024 bits). The existing RAW is based on optimisation of energy efficiency and the time slot duration is fixed [WLC⁺15]. It can be observed that the proposed RAW performs better than the existing one with 113.3% and 63.3% improvement for packet size=512 and 1024 bits respectively. The curves of both two packet sizes are concave and the peak point is at $N=90$. So the highly dense networks require grouping to decrease collision probability, and for the network with 6000 devices, the most efficient grouping strategy is 90 devices in one group and 67 group in total. The adaptive time slots can decrease the wake-up power, which is a way to reduce the energy consumption and increase the number of packets being sent in a certain time, thus the proposed RAW outperforms the existing RAW.

When the number of devices per group is low, the signalling energy consumption would be high to achieve the whole network communications since the scheduling information needs to send multiple times after a short time. So with the increment of group scale, the signalling energy consumption would decrease, which is a dominant factor to increase the energy efficiency. However, if the number of devices per group is too large, the collision probability would be high due to contention that leads to consume more energy and reduce throughput, which are two parameters for the cause of low efficiency, thus the trend of two curves will go down. Since the number of bits that are sent for a time period increases with the increment of packet size based on the same number of devices, the energy efficiency of the group with 1024 bits per packet is higher than that of 512 bits.

Fig. 3.11 shows the average delay for one RAW with two packet sizes as it varies along diverse number of devices per group. The delay is the waiting time for devices from wake-up to access. It can be seen that the proposed RAW reduces in general 53.4% and 37.9% in uplink average delay for packet size = 512 bits and 1024 bits respectively. The delay of existing RAW for both packet sizes are nearly same due to the same

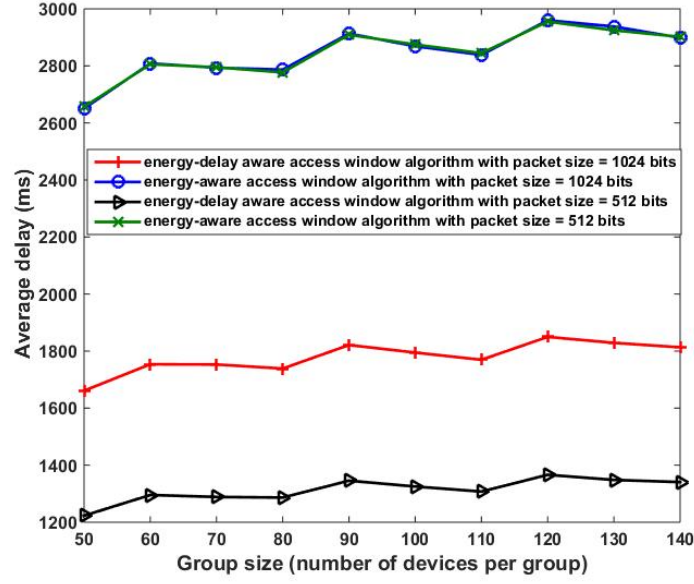


Fig. 3.11: Average delay comparison with different groups sizes between energy-delay aware access window and energy-aware access window.

duration and number of time slots. Since the transmission time increases with the packet size in the proposed algorithm, the average delay of 1024 bits is higher than the one of 512 bits. The more number of devices will lead to longer duration of RAW in order to avoid collision, thus the average delay will increase along the increment of the number of devices per group. In addition, the adaptive duration of time slot can alleviate idle listening time, so the speed of rising for the proposed RAW is lower than the existing one. However, sometimes, the increasing rate of the number of time slots is lower than the increasing rate of group size, so the curves are not smooth, for instance the device number changing from 60 to 80, from 90 to 110 and from 120 to 140.

3.5 Summary

In this chapter, the RAW size control is proposed to optimise uplink communications energy efficiency for IEEE 802.11ah networks via adaptive window size for different group sizes and application types. The optimisation problem is formulated by probability the-

ory to describe various status that a device may fall into when transmitting a packet through one RAW. On account of that, overall energy consumption and throughput are estimated to contribute to the energy efficiency. To maximise the energy efficiency, optimal solution is derived by applying Hill Climbing, Simulated Annealing and Gradient Descent.

The simulation results show that the main factor that dominates energy efficiency varies over the number of devices or time slots in one RAW. With the increment of number of devices, the primary aspect is from signalling information energy to collision waste, while for raising RAW duration, the crucial element changes from collision waste to wake-up energy. The balanced combination (90 devices with 180 time slots) can achieve superior energy efficiency.

The dynamic energy-aware access window algorithm, which sets the adaptive number of slots in one window based on group sizes, can improve the uplink energy efficiency and delivery ratio. The energy-delay aware access window algorithm, which sets the joint optimal RAW duration and internal time slot duration, can lead to improvement of energy efficiency and delay, as it can decrease the time period of wake-up mode and contention for a group. Thus the novel RAW control can lower the idle listening power and increase the number of packets sent in a certain time for uplink communications.

Chapter 4

RAW Retransmission Control

This chapter focuses on the retransmission control of the uplink channel access in IEEE 802.11ah. A novel retransmission mechanism for collided devices is presented to improve the channel utilisation and packet delivery ratio. Two adaptive access window algorithms in retransmission control are proposed for AP to determine RAW size based on the new retransmission mechanism to optimise energy efficiency as well as delay. Section 4.1 presents the motivation of retransmission control in channel access of IEEE 802.11ah. Section 4.2 proposes a novel retransmission mechanism. The optimisation problem based on novel retransmission is formulated in Section 4.3. Finally, in Section 4.4, RAW retransmission control is proposed to improve energy efficiency for IEEE 802.11ah. Within Section 4.4, two novel algorithms in the retransmission control for IEEE 802.11ah networks are proposed to improve energy efficiency: (1) energy-aware access window with retransmission algorithm for adapting the number of slots per window for diverse groups sizes to improve energy efficiency; (2) energy-delay aware access window with retransmission algorithm for adapting dynamic slots number and internal slot interval for diverse group sizes and application types to achieve joint optimisation in energy efficiency and delay.

4.1 Motivation

Due to the random selection in RAW of IEEE 802.11ah uplink communications, there exists empty slots where no device chooses, while some slots are chosen by multiple devices which results in collision. In addition, empty slots in a window increase the idle listening time of devices, which reduce the throughput and add the wake-up energy consumption for devices. To reuse the empty slots to improve the throughput of one window, a novel retransmission mechanism is required for collided devices to alleviate contention and improve channel utilisation. As the window size has the impact on energy efficiency, an adaptive window size is needed to achieve high energy efficiency. In the following work, a novel retransmission mechanism is designed to improve the channel utilisation by retransmitting collided packets in the subsequent slot. On account of that, two adaptive algorithms are proposed to improve the energy efficiency.

4.2 System Model

An IEEE 802.11ah based network as one AP with 6000 devices is considered. The devices are randomly clustered into several groups. Each group is assigned to a RAW to access channel. In IEEE 802.11ah uplink communications, for each RAW, there are M time slots and N devices limited by the lowest and highest AID of devices indicating the location, traffic, type, and energy saving mode [KLKG15]. The devices which have buffered data for the AP randomly select one of the uplink time slots in their allocated RAW and attempt to access the channel. To alleviate the empty slot waste, a novel retransmission mechanism is proposed to improve the channel utilisation by providing one more chance for collided devices to retransmit packet in the next slot within the allocated RAW. The detailed access process via RAW is shown in Fig. 4.1.

As an example shown in Fig. 4.2, after random selection, if there is only one device in a slot, it could access directly as Device 1 transmits packet in Slot 1 directly without

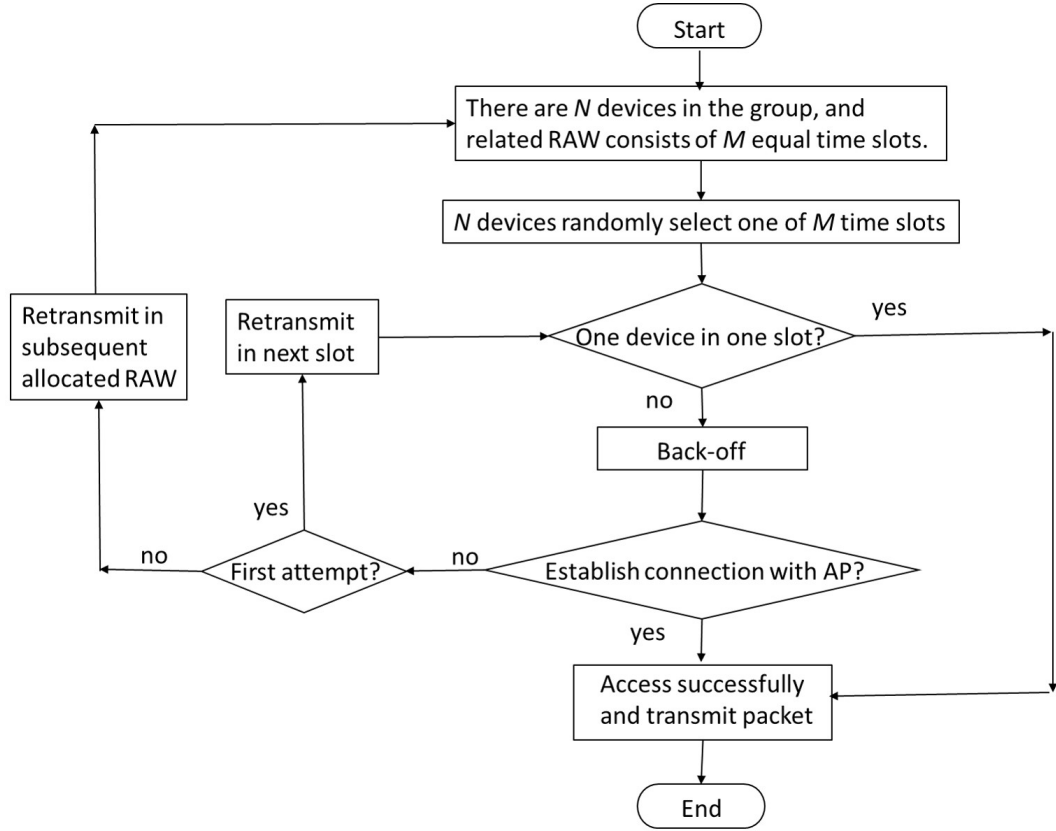


Fig. 4.1: Uplink channel access in IEEE 802.11ah with retransmission.

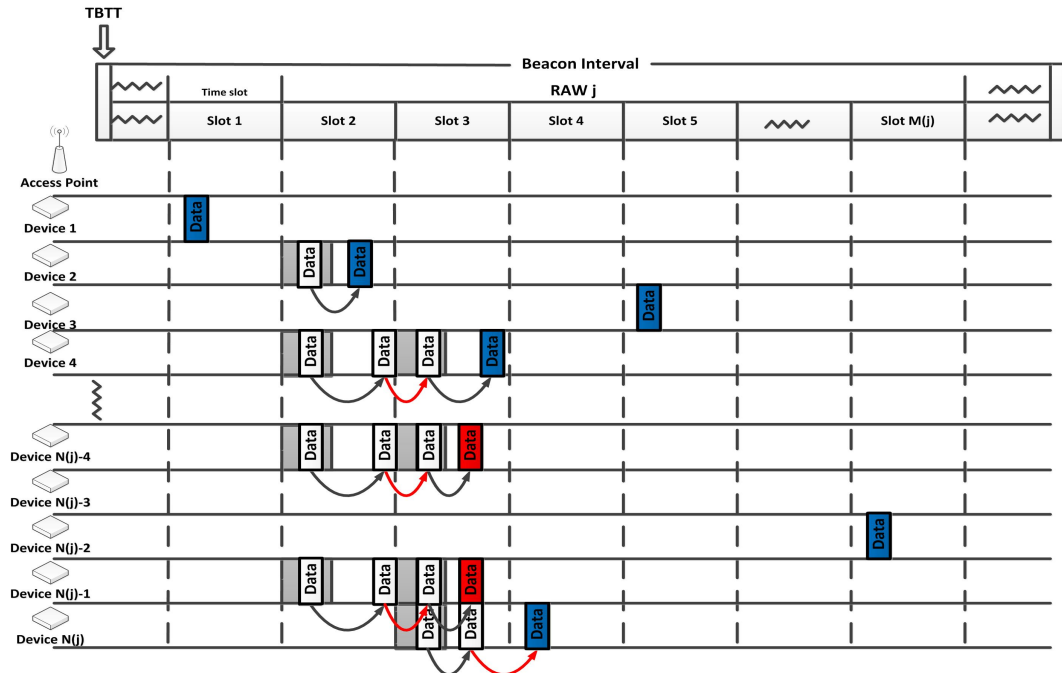


Fig. 4.2: Example of uplink RAW operation in IEEE 802.11ah with retransmission.

contention, and the same for Device 3 in Slot 5 and Device $N(j) - 2$ in Slot $M(j)$. When there are more than one devices choosing the same time slot, for example, Device 2, Device 4, Device $N(j) - 4$, and Device $N(j) - 1$ in Slot 2, they would come into the back-off stage to avoid collision by doubling contention window and attempting again until reaching the slot boundary. If successfully accessing the channel, the device requests uplink communication by sending a PS-poll message to the AP. The AP responds with an ACK to confirm connection. After the first handshake, the device transmits the buffered data frame and waits for the ACK from the AP [Par13]. It is assumed that if not accessing the channel, it would retransmit in the next slot, for instance, when Device 2 has accessed the channel in Slot 2, Device 4, Device $N(j) - 4$ and Device $N(j) - 1$ retransmit in Slot 3, which needs to contend with Device $N(j)$. But when they can not retransmit successfully in the following slot, they need to retransmit in the subsequent allocated RAW, such as Device $N(j) - 4$ and Device $N(j) - 1$ in Slot 3.

The process is repeated, one RAW by one RAW, until the end of beacon frame as shown in Section 2.1.3 and Fig. 2.3.

4.3 Problem Formulation

In this section, energy efficiency maximisation problem for IEEE 802.11ah uplink communications is formulated based on the proposed retransmission mechanism. The process of devices to access channel in IEEE 802.11ah is formulated by Markov Chain, and then the energy efficiency is derived.

For random selection, the states of each time slot are different, and retransmission mechanism makes it dependent on the state of the previous slot, so Markov Chain is applied to monitor the accessing process of each time slot in one RAW.

The process in Markov Chain is represented by three parameters k , n_k , s_k , where k is the index of time slot in one RAW; n_k shows there are n_k devices to choose the k th time slot; s_k is the number of devices accessing channel successfully, which is illustrated in Fig. 4.3. The initial state is $(0, n_0, 0)$. Subsequently, for the first slot, there are n_1 devices choose this slot, resulting in two states: (1) no device accesses the channel due to collision; (2) one device accesses the channel. The states of the following slots are based on the previous slot. If no device accesses channel in the previous slot, the contended devices in k th is $(n_k + n_{(k-1)})$, otherwise it is $(n_k + n_{(k-1)} - 1)$.

The transition probability of adjacent states can be denoted as

$$P_{xy} = \begin{cases} P_{d.n_y} P_{s.n_y}, & \text{if } (x = 0, 0 < n_y < N, s_y = 1) \\ P_{d.n_y} (1 - P_{s.n_y}), & \text{if } (i = 0, 0 < n_y < N, s_y = 0) \\ P_{d.n_y} P_{s.(n_y + n_x - s_x)}, & \text{if } (i > 0, 0 < n_y < (N - \sum_{k=1}^x n_k), s_y = 1) \\ P_{d.n_y} (1 - P_{s.(n_y + n_x - s_x)}), & \text{if } (i > 0, 0 < n_y < (N - \sum_{k=1}^x n_k), s_y = 0) \\ 0, & \text{otherwise} \end{cases} \quad (4.1)$$

where P_{xy} is the probability to transfer from x th slot to y th slot; $P_{d.n_y}$ is the probability that there are n_y devices choose the same time slot; $P_{s.n_y}$ is the probability of successful access.

According to [PHL14], there are two cases for a device to transmit uplink packet successfully in a slot.

- Case 1: the time slot is selected by only one device. Thus this device could occupy the whole slot to transmit packet directly without contention.
- Case 2: the time slot is selected by multiple devices. They would come into the back-off stage to avoid collision by doubling contention window. In addition, the collision does not occur if one of the devices could access the channel in the first

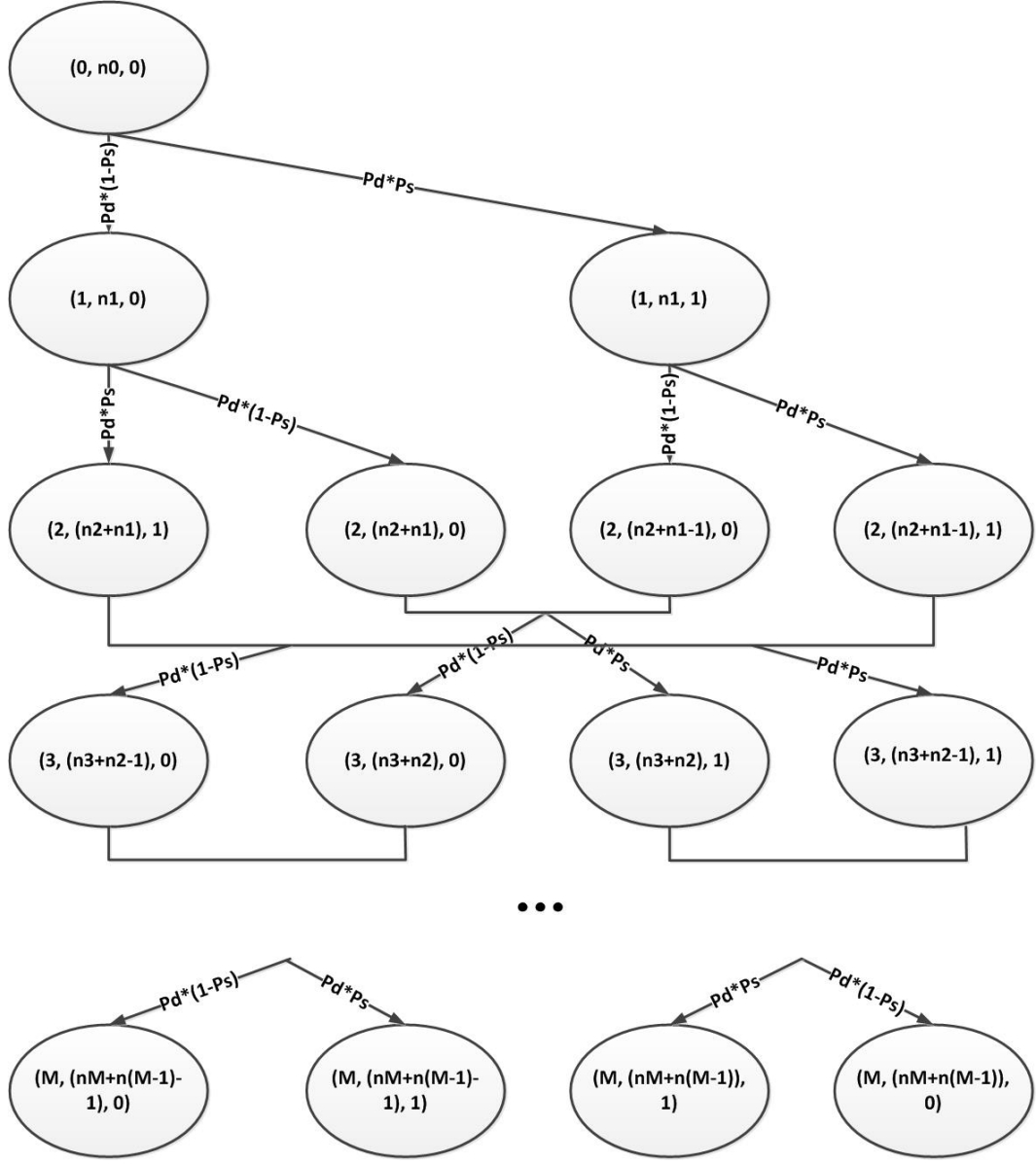


Fig. 4.3: Markov Chain of dependency between time slots.

back-off stage. If the devices can not access in the selected slot, they will move to the next slot to re-attempt.

For one time slot in RAW, the probability that there are n_k devices after random selection is

$$P_{d.n_k} = \binom{N}{n_k} \left(\frac{1}{M}\right)^{n_k} \left(1 - \frac{1}{M}\right)^{N-n_k}, \quad (4.2)$$

where M is the number of time slots in one RAW; N is the number of devices in one group to attempt to access channel via one RAW; n_k is the number of devices to choose the k th time slot.

So based on two successful cases, the transmission probability can be denoted as

$$P_{s.n_k} = \begin{cases} 1, & \text{if } (n_k = 1) \\ P_{back-off}(n_k), & \text{if } (n_k > 1) \end{cases}, \quad (4.3)$$

where $n_k = 1$ denotes the situation as the Case 1; $(n_k > 1)$ is related to Case 2; $P_{back-off}(n_k)$ is the probability of accessing channel in the first back-off stage as Case 2.

For Case 2, these i devices in the same slot will go to the back-off stage. The probability of one device building connection with AP through minimum contention window as the first back-off stage is obtained alike that this device occupies the front slot without other devices, which is denoted as

$$P_{back-off}(n_k) = \sum_{x=0}^{W_{\min}-1} \left\{ \prod_{0}^x \left[1 - \frac{1}{W_{\min}} \left(1 - \frac{x}{W_{\min}} \right)^{n_k-1} \right] \right\} \frac{1}{W_{\min}} \left(1 - \frac{x+1}{W_{\min}} \right)^{n_k-1}, \quad (4.4)$$

where W_{\min} is the minimal size of contention window.

The total number of packets that can be sent in one RAW is

$$\sum_0^M s_k = \sum_0^M s_{k.1} + \sum_0^M s_{k.2}, \quad (4.5)$$

where $\sum_0^M s_{k.1}$ is the number of packets sent as Case 1; $\sum_0^M s_{k.2}$ is the number of packets sent as Case 2.

In order to estimate the number of transmitted packets, the average number of packets that can be transmitted successfully in one each slot is formulated as

$$\begin{aligned}
s_1 &= \sum_{n_1=1}^N P_{d,n_1} P_{s,n_1} \\
s_2 &= \sum_{n_2=1}^{N-n_1} \sum_{n_1=1}^N \underbrace{[P_{d,n_1}(1 - P_{s,n_1})P_{d,n_2}]}_{\varepsilon_{21}} P_{s,(n_2+n_1)} + \underbrace{[P_{d,n_1}P_{s,n_1}P_{d,n_2}]}_{\varepsilon_{22}} P_{s,(n_2+n_1-1)} \\
s_3 &= \sum_{n_3=1}^{N-n_1-n_2} \sum_{n_2=1}^{N-n_1} \sum_{n_1=1}^N \underbrace{[(\varepsilon_{21}(1 - P_{s,(n_3+n_2)}) + \varepsilon_{22}(1 - P_{s,(n_3+n_2-1)}))P_{d,n_3}]}_{\varepsilon_{31}} P_{s,(n_3+n_2)} \\
&\quad + \underbrace{(\varepsilon_{21}P_{s,(n_3+n_2)} + \varepsilon_{22}P_{s,(n_3+n_2-1)})P_{d,n_3}}_{\varepsilon_{32}} P_{s,(n_3+n_2-1)} \\
&\quad \dots \\
s_k &= \sum_{n_k=1}^{N-\sum_{x=1}^{k-1} n_x} \sum_{n_{(k-1)}=1}^{N-\sum_{x=1}^{k-2} n_x} \dots \sum_{n_1=1}^N \\
&\quad \underbrace{[(\varepsilon_{(k-1)1}(1 - P_{s,(n_k+n_{(k-1)})}) + \varepsilon_{(k-1)2}(1 - P_{s,(n_k+n_{(k-1)}-1)}))P_{d,n_k}]}_{\varepsilon_{k1}} P_{s,(n_k+n_{(k-1)})} \\
&\quad + \underbrace{(\varepsilon_{(k-1)1}P_{s,(n_k+n_{(k-1)})} + \varepsilon_{(k-1)2}P_{s,(n_k+n_{(k-1)}-1)})P_{d,n_k}}_{\varepsilon_{k2}} P_{s,(n_k+n_{(k-1)}-1)}
\end{aligned} \tag{4.6}$$

The energy consumption for a group of devices to access channel and transmit packets in one RAW is estimated based on different states that devices may fall into with various probability, which is denoted by

$$E_t = E_{t1} \sum_0^M s_{k,1} + E_{t2} \sum_0^M s_{k,2} + E_c(N - \sum_0^M s_k) + E_{wake-up} M \tau N, \tag{4.7}$$

where E_{t1} is the energy consumption when transmitting a packet successfully as Case 1; E_{t2} is the energy consumption when transmitting a packet successfully as Case 2; E_c is the energy waste when there is collision both in its slot and the next slot so that it needs to retransmit in another allocated RAW; $E_{wake-up}$ is the idle listening energy in one RAW, which is the energy consumed when it is in the wake-up mode; and τ is the time duration of one time slot.

The size of RAW also has the impact on the energy consumption of transmitting

signalling information, because for a short RAW duration, the signalling information of AP to each device will be high due to the scheduling information that needs to be transmitted multiple times in a short time. In addition, if the group size is small, it also needs massive scheduling information to realise network communications. So the energy consumption of signalling information is related to N and M :

$$E_{signal} = \frac{\alpha}{M} \times \frac{\beta}{N}, \quad (4.8)$$

where α is the parameter indicating traffic and β is the parameter related to overall number of devices in the scenario.

The overall energy consumption for a group of devices to access within one RAW consists of transmission energy and signalling energy, which is denoted by

$$E_{overall} = E_t + N E_{signal}. \quad (4.9)$$

Throughput for a RAW is the ratio of number of bits that can be transmitted in one RAW to the RAW duration, which is formulated as

$$R = \frac{\sum_0^M s_k \times \gamma}{\tau M}, \quad (4.10)$$

where γ is the packet size. $\sum_0^M s_k \times \gamma$ is the total length of packets in bit that can be transmitted for N devices in M time slots. τM is the time duration of one RAW.

Energy efficiency for one RAW is evaluated by the throughput it provides and the overall energy consumption including transmitting energy and signalling energy. Thus

the energy efficiency is

$$EE(M, N) = \frac{R}{E_{overall}} = \frac{\gamma \sum_0^M s_k}{\tau M(E_t + NE_{signal})}. \quad (4.11)$$

Thus energy efficiency is a function related to the number of devices involved (N) and time slot in one RAW (M, τ). The maximisation of energy efficiency can be realised by finding optimal M and τ based on diverse groups.

4.4 RAW Retransmission Control

4.4.1 Energy-aware Access Window with Retransmission Algorithm

In this section, an energy-aware access window with retransmission algorithm is proposed based on the novel retransmission mechanism.

The energy efficiency in Equation 4.11 can be expressed as

$$EE = \frac{\gamma(\tau M)^{-1} \sum_0^M s_k}{E_{t1} \sum_0^M s_{k.1} + E_{t2} \sum_0^M s_{k.2} + E_c(N - \sum_0^M s_k) + E_{wake-up}N + \frac{\alpha\beta}{M}}. \quad (4.12)$$

Let $\psi = \sum_0^M s_k$ and $E_{t,avg}$ be the average energy consumption to send a packet successfully in a slot, the energy efficiency can be transferred to

$$EE = \frac{\gamma\psi}{\tau[ME_{t,avg}\psi + ME_c(N - \psi) + E_{wake-up}MN + \alpha\beta]}. \quad (4.13)$$

ψ is a function related to P_{d,n_k} and P_{s,n_k} which can be denoted as $\psi = \sum P_{d,n_k} \times P_{s,n_k}$, which is a monotone increasing function along with the increment of the number of time slots, because the amount of packets that can be sent increases with the increment of the

RAW size. For the denominator, $ME_{t_{avg}}\psi + ME_c(N - \psi)$ is a decreasing function, since ψ increase with enlarging RAW duration and $E_c \geq E_{t_{avg}}$. In addition, $E_{wake-up}MN$ is an increasing function for M , thus the denominator is a convex function and the EE is concave with a maximum value.

The optimal RAW size for the different group scales based on the novel retransmission mechanism is found to maximise the uplink energy efficiency by applying Gradient Descent approach, a fast algorithm to find the optimum of large search space as shown in Algorithm 6.

Algorithm 6 Gradient Descent Energy-aware Access Window with Retransmission Algorithm

- 1: **Step 1: AP recognises the size for each group (the number of devices in one group as N).**
 - 2: **Step 2: Estimate optimal RAW size for a certain group as M .**
 - 3: **loop**
 - 4: Initialise M_{old} and M_{new} as two random numbers.
 - 5: $EE'(M) = \frac{\partial(-EE(M,N))}{\partial M}$
 - 6: **while** $|EE(M_{old}) - EE(M_{new})| \geq precision$ **do**
 - 7: $\partial = 0.01$
 - 8: $M_{old} = M_{new}$
 - 9: $M_{new} = M_{old} - \partial \times EE'(M)$
 - 10: **end while**
 - 11: return M
 - 12: **end loop**
 - 13: **Step 3: AP sets the window size as M equal time slots for this group. The devices fall into sleep mode to save energy, and wake up until coming to the allocated window.**
 - 14: **Step 4: N devices in the group try to establish connection with AP by randomly selecting one of M time slots in the window and attempt to access channel.**
 - 15: N devices in the group choose one of M slots in the window randomly.
 - 16: Devices attempt to access the channel to build connection with AP as Case 1 and Case 2.
 - 17: When the device could not access in the selected slot, re-attempt to access in the following slot. The operation is the same as in the previous one.
 - 18: If the device still fails to access the channel in the next slot, the device needs to wait for the next allocated RAW for the group to re-access.
-

Algorithm 6 is a standard Gradient Descent approach to find the optimal RAW size for a group of devices. The first solution is a random value M . The step that enlarges the existing solution is the gradient of the energy efficiency $EE(M_{old})$. Then the subsequent outcomes are compared with the previous value. When the upcoming one is better, the solution is updated by the new one. The process is done iteratively, and ends at the optimal energy efficiency.

4.4.2 Simulation Results

In this section, the optimisation for RAW is evaluated in Matlab. A scenario with one AP and 6000 devices as described in the system model is considered. The energy-aware access window with retransmission algorithm is applied to the AP and the novel retransmission mechanism is used to collided devices. The optimal window size is found based on the setting of 200 to α and β respectively. Since the objective of the RAW control is to optimise energy efficiency and the novel retransmission mechanism can improve the number of transmitted packets, the energy efficiency and delivery ratio for different group sizes are simulated. During one RAW, each device has exactly one uplink packet to transmit during one beacon. The main simulation parameters are given in Table 4-A.

Table 4-A: Simulation Parameters for Energy-aware Access Window with Retransmission in IEEE 802.11ah Uplink Communications with Fixed Slot Interval

Parameter	Value	Parameter	Value
Frequency	0.9 GHz	Data rate	100 kbps
Case 1 transmit power	1.346 mw	Case 2 transmit power	2.5 mw
Collision power	3.0 mw	Idle listening power	0.001 mw
Slot duration	31.1 ms	Packet length	1024 bits
Min contention window	8	Max contention window	1024

Fig. 4.4 shows the energy efficiency for retransmission mechanism varying over diverse

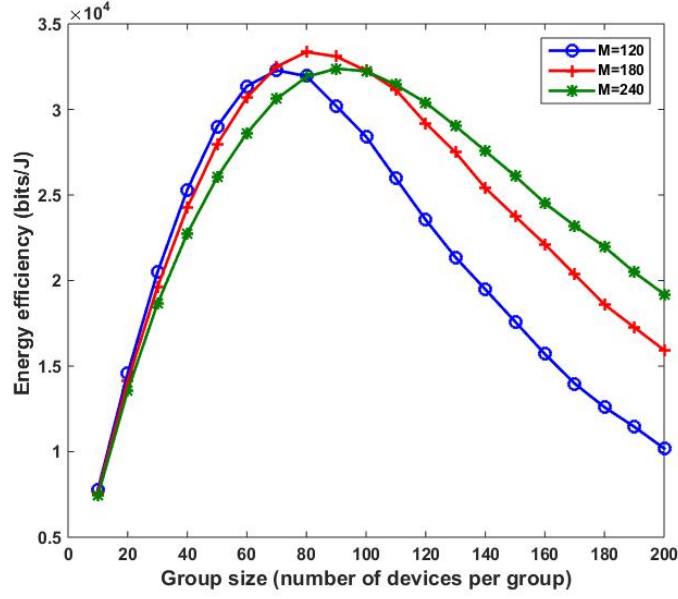


Fig. 4.4: Energy efficiency per RAW with different group sizes for three window sizes ($M=120, 180, 240$).

number of devices per group based on three different durations of one RAW ($M=120, 180, 240$). It can be observed that the curves are concave with the one optimal value. The maximal energy efficiency of three window sizes are related to different group sizes. When the number of time slots in RAW is fixed, if the group size is small, the energy efficiency for three RAWs goes up with the increment of the number of devices since the signalling energy consumption would decrease for less scheduling information that needs to be sent as for whole network communications. Then, three curves reach the peak points, which are forwarding along the RAW sizes as $N=70$ for $M=120$, $N=80$ for $M=180$ and $N=100$ for $M=240$, because the optimal capacity of the large RAW is higher than the small one. After the peaks, the trends of three curves decline, and the rate of abatement is higher when the duration is shorter, since high collision probability lowers the data rate and enlarges energy consumption. It is also the reason for worse performance with short RAW duration for a big group size with high slop in the Fig. 4.4.

Fig. 4.5 shows the energy efficiency based on retransmission mechanism with three

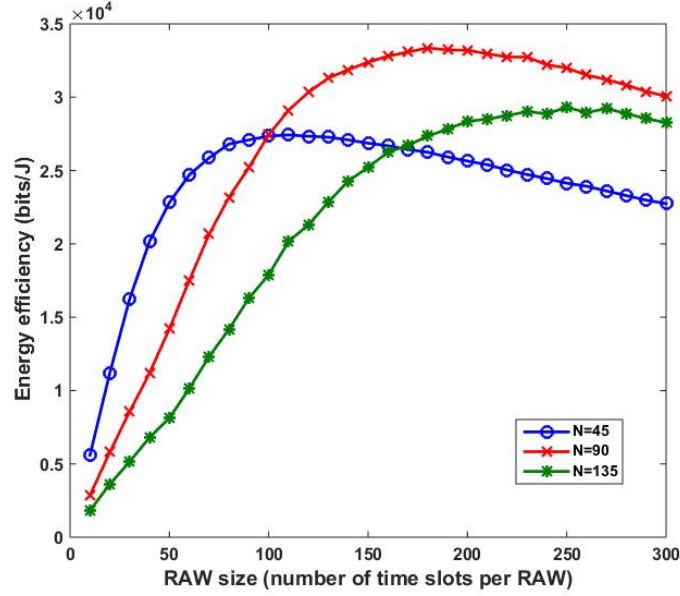


Fig. 4.5: Energy efficiency per RAW with different RAW sizes for three group sizes ($N=45, 90, 135$).

group sizes ($N=45, 90, 135$) as it varies along diverse number of time slots. All three curves are concave with a maximum value along with the diverse RAW sizes. The optimal RAW size for various group sizes is not same. In addition, the best matched window size increases with the number of devices per group. When RAW duration is fixed for different groups, if the number of time slots is small, the energy efficiency of three scenarios is low and the trends of the three curves all go up, since collision probabilities are high and decreasing with enlarging the window size, where it is also the reason why the increasing rates of these three curves are negatively correlated to group scales. At this stage, collision is the main factor for the data rate and energy consumption. The optimal window sizes as the peak points of uplink energy efficiency for three groups increase with the number of devices, due to higher capacity for larger window. However, if the RAW duration is too large, after the peak value, the energy efficiency would drop due to long time in the wake-up mode, which means the idle listening energy of devices would be high. The amount of energy consumption on signalling information is opposite to the group size, so the energy efficiency decreasing speed of small group size is higher than that of larger groups.

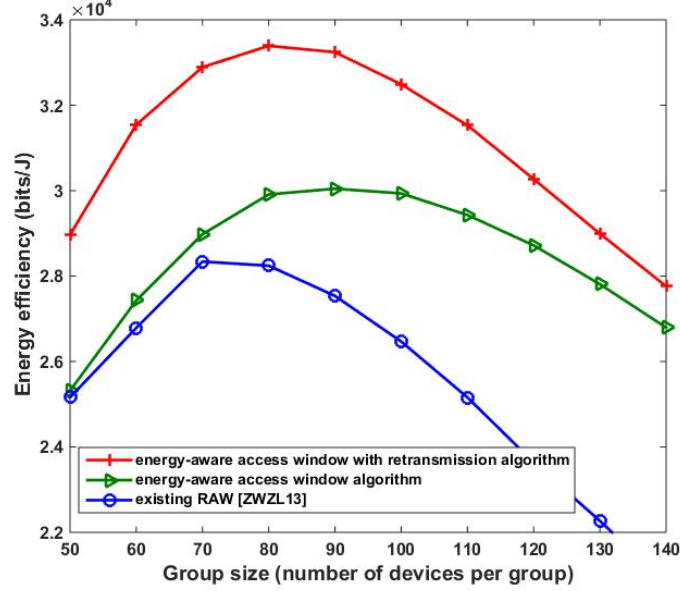


Fig. 4.6: Energy efficiency comparison per RAW with different group sizes among energy-aware access window with retransmission, energy-aware access window and existing window in [ZWZL13].

Fig. 4.6 shows the energy efficiency comparison between the proposed algorithm and the existing RAW. The proposed RAW is to set the best matched window size based on group size to achieve the optimal energy efficiency based on the novel retransmission mechanism that the collided devices retransmit in next slot, while the legacy mechanism as energy-aware access window algorithm is to adapt window size and retransmit in another allocated RAW when there is a collision as in Chapter 3. According to simulation results, the uplink energy efficiency of proposed RAW improves 12.3% in general when comparing with the results of adaptive window without retransmission mechanism.

With random selection in uplink communication, there are many empty slots without device to choose. The proposed algorithm is to retransmit in the next slot for collided devices in a crowded slot (selected by more than one device), which can reuse the empty slots, while the existing control is to retransmit in another allocated RAW, so there are more packets can be transmitted in the proposed RAW, leading to high energy efficiency.

When the group size is small, the energy efficiency increases along with the rising of the number of devices, since the scheduling information do not need to be sent multiple times which lowers the signalling energy consumption. In addition, the large group size brings more empty time slots in this stage, so the improvement is more distinct with increasing of the number of devices per group. However, the trend declines after peak due to more collision with the high number of devices. The higher active power consumption for larger group is another reason for decline.

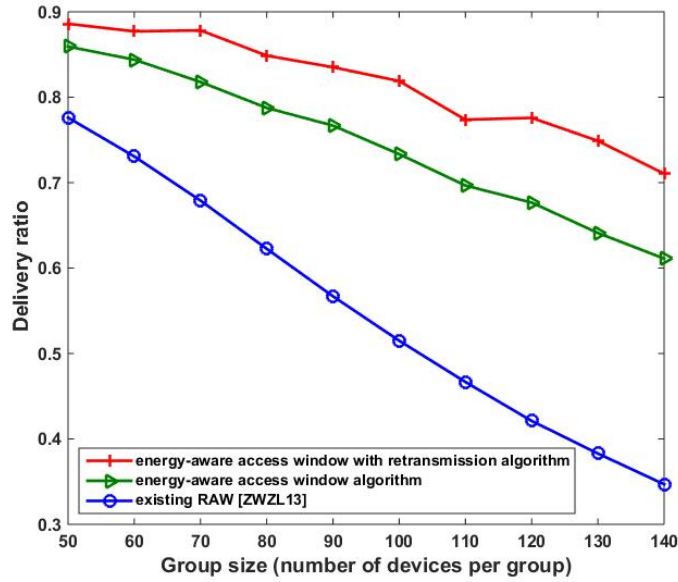


Fig. 4.7: Packet delivery ratio comparison per RAW with different group sizes among energy-aware access window with retransmission, energy-aware access window and existing window in [ZWZL13].

Fig. 4.7 shows the packet delivery ratio comparison between the proposed algorithm and the existing RAW in [ZWZL13]. It can be observed that the proposed algorithm could improve in general 7.5% comparing with the adaptive window without retransmission mechanism (energy-aware access window algorithm). Reusing empty slots in retransmission mechanism makes more packets being sent in one window. In other words, the ratio of the transmitted packets number to the number of time slots is higher for the proposed algorithm than the existing mechanism. With the rising number of devices per

group, the trends of three RAWs go down due to higher collision probability which leads to more consumed energy and less transmitted packets. The number of empty time slots would decrease through retransmission control, so the rate of decrement in the proposed one is lower than the existing controls and the improvement is larger for higher density of devices per group.

Simulation results demonstrate the proposed energy-aware access window with novel retransmission algorithm could bring superior energy efficiency and delivery ratio for IEEE 802.11ah uplink communications.

4.4.3 Energy-delay Aware Access Window with Retransmission Algorithm

In this section, an energy-delay aware access window with retransmission is proposed to jointly optimise energy efficiency and delay for IEEE 802.11ah networks.

Let $\psi = \sum_0^M s_k$ and E_{t_avg} be the average energy consumption to send a packet successfully in a slot, the energy efficiency can be simplified as

$$EE = \frac{\gamma\psi\tau^{-1}}{ME_{t_avg}\psi + ME_c(N - \psi) + E_{wake-up}M\tau N + \alpha\beta}. \quad (4.14)$$

ψ is a function related to $P_{d_n_k}$ and $P_{s_n_k}$ which can be denoted as $\psi = \sum P_{d_n_k} \times P_{s_n_k}$, which is a monotone increasing function along with the increment of the number of time slots, because the amount of packets that could be sent increases with the increment of the RAW size. For denominator, $ME_{t_avg}\psi + ME_c(N - \psi)$ is a decreasing function, since ψ increase with enlarging RAW duration and $E_c \geq E_{t_avg}$. In addition, $E_{wake-up}M\tau N$ is an increasing function for M , thus denominator is a convex function and the EE is concave with a maximum value.

In order to guarantee the transmission, the time slots can be determined by device types. Packet size is a main factor for adaptive time slots, which can be denoted as

$$\tau \geq \frac{\gamma}{v} + \tau_{back_off}, \quad (4.15)$$

where v is the transmission rate of IEEE 802.11ah and τ_{back_off} is the back-off time when more than one devices choose the same time slot.

The optimal RAW duration for different group scales based on novel retransmission mechanism is found to maximise the uplink energy efficiency and decrease delay by applying Gradient Descent, a fast algorithm to find the optimum of large search space as shown in Algorithm 7.

Algorithm 7 is a standard Gradient Descent approach to find the optimal RAW size and slot duration. The optimal solution M is got through adding a gradient value to the input. Then the channel access for the devices are done through the window with M slots.

4.4.4 Simulation Results

In this section, the performance of the optimisation algorithm for RAW is evaluated in Matlab. An IEEE 802.11ah network as described in the system model is considered. The energy-delay aware access window with retransmission algorithm is applied to the AP and the novel retransmission mechanism is used for collided devices. The optimal value is found based on the setting of 200 to α and β respectively. Each participated device has exactly one packet to transmit for uplink communications during one RAW. The main simulation parameters are given in Table 4-B.

Fig. 4.8 shows the uplink energy efficiency varying over diverse group sizes based

Algorithm 7 Gradient Descent Energy-delay Aware Access Window with Retransmission

- 1: **Step 1:** AP detects the devices type and the number of devices in the group.
 - 2: **Step 2:** The uplink time slot durations are set based on the type of devices, which are the constraints
 - 3: uplink time slot duration \geq transmit time + back_off time as $\tau \geq \frac{\gamma}{v} + \tau_{back_off}$.
 - 4: **Step 3:** Estimate optimal uplink RAW size for a certain group.
 - 5: **loop**
 - 6: Initialise M_{old} and M_{new} as two random numbers.
 - 7: $EE'(M) = \frac{\partial(-EE(M, N, \tau))}{\partial M}$
 - 8: **while** $|EE(M_{old}, \tau) - EE(M_{new}, \tau)| \geq precision$ **do**
 - 9: $\partial = 0.01$
 - 10: $M_{old} = M_{new}$
 - 11: $M_{new} = M_{old} - \partial \times EE'(M)$
 - 12: **end while**
 - 13: return M and τ
 - 14: **end loop**
 - 15: **Step 4:** Set RAW as M time slots for this group. The devices fall into sleep mode and wake up when coming to their allocated window.
 - 16: **Step 5:** N devices randomly select one of M time slots in RAW and attempt to do uplink communications with AP.
 - 17: N devices in the group choose one of M slots randomly.
 - 18: Devices attempt to access channel to establish connection with AP as Case 1 and Case 2.
 - 19: When the device could not access in its slot, re-attempt in the following slot. The operation is same as in the previous one.
 - 20: If the device still could not access in next slot, the device needs to wait for next allocated RAW to re-access.
-

Table 4-B: Simulation Parameters for Energy-delay Aware Access Window with Retransmission in IEEE 802.11ah Uplink Communications with Dynamic Slot Interval

Parameter	Value	Parameter	Value
Frequency	0.9 GHz	Data rate	100 kbps
Case 1 transmit power	1.346 mw	Case 2 transmit power	2.5 mw
Collision power	3.0 mw	Back-off time slot duration	9 μ s
Min contention window	8	Max contention window	1024

on two different packet sizes (512 bits and 1024 bits). The proposed RAW is to set the best matched window size and internal slot interval based on groups to achieve the optimal energy efficiency with the novel retransmission mechanism as the the collided

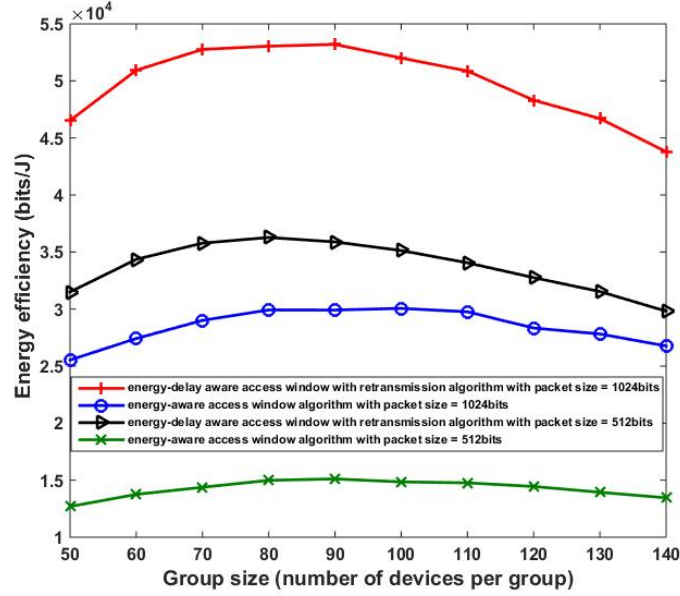


Fig. 4.8: Energy efficiency comparison per RAW with different group sizes between energy-delay aware access window with retransmission and energy-aware access window with retransmission.

devices retransmit in the next slot. The legacy RAW in Chapter 3 is to set the adaptive number of slots based on the optimisation of energy efficiency and the retransmission is in another allocated RAW when there is a collision [WLC⁺15]. It can be observed that the proposed RAW performs better than the existing one with 113.3% and 63.3% improvement for packet size=512 and 1024 bits respectively.

For random access in uplink communication, there are many empty slots with no device to choose. The proposed RAW with retransmission scheme is to retransmit in the next slot for collided devices in the crowded slot (selected by more than one device), which could reuse the empty slots, so there are more packets can be transmitted in the proposed RAW, leading to high energy efficiency. The adaptive time slots can decrease the wake-up power, which is a way to reduce the energy consumption, thus the proposed control could outperform the existing control.

When the number of devices is low, the signalling energy consumption would be

high to achieve whole network communications, since scheduling information needs to be sent multiple times after a short time. So with the increment of group scale, the signalling energy consumption would decrease, which is a dominant factor to increase the energy efficiency. However, if the number of devices per group is too large, the collision probability would be high that leads to more consumed energy and less throughput, which are the two parameters for low efficiency, resulting in the trend of curves will go down. Since the throughput increases with the increment of packet size based on the same number of devices, the energy efficiency of 1024 bits per packet is higher than that of 512 bits.

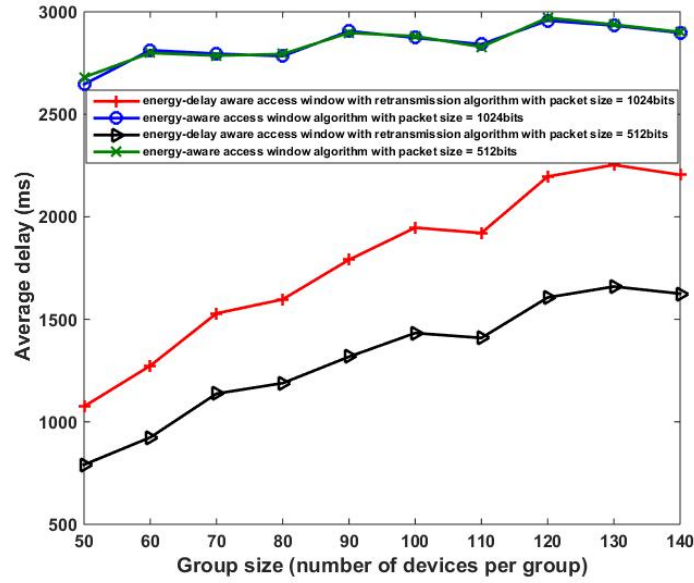


Fig. 4.9: Average delay comparison per RAW with different group sizes between energy-delay aware access window with retransmission and energy-aware access window with retransmission.

Fig. 4.9 shows the uplink delay with two packet sizes as it varies along diverse number of devices per group. The proposed RAW reduces 53.4% and 37.9% in the uplink delay for packet size=512 bits and 1024 bits respectively. The novel retransmission mechanism can lead to more packet being transmitted in one RAW so that the average delay for one RAW is lower than the existing control. The adaptive slot interval could alleviate

the time waste, which is another reason for the decreasing delay.

The delay of the existing RAW for both packet sizes are same due to the same duration and number of time slots. Since the transmission time increases with the packet size in the proposed control algorithm, the average delay of 1024 bits is higher than the one of 512 bits. In addition, more number of devices will lead to longer duration of RAW in order to avoid collision, thus the average delay would increase along the increment of the number of devices. However, sometimes the increasing rate of the number of time slots is lower than the increasing rate of devices, so the curve is not smooth such as the number of devices changing from 100 to 110.

Simulation results demonstrate the proposed algorithm can bring superior energy efficiency and delay for IEEE 802.11ah uplink communications.

4.5 Summary

In this chapter, the novel retransmission mechanism is proposed to reuse the empty slots to improve channel utilisation. The energy efficiency optimisation problem is built based on Markov Chain and probability theory to monitor the access process and dependency of each time slot. Then, the transmission probabilities is evaluated for various states that a device may fall into when sending a packet during one RAW. On account of that, the overall energy consumption and the throughput are estimated to contribute to energy efficiency.

The RAW retransmission control is proposed to optimise energy efficiency. The energy-aware access window with retransmission algorithm is proposed for IEEE 802.11ah based networks to optimise uplink energy efficiency through adapting RAW duration for different group sizes. The energy-delay aware access window with retransmission algo-

rithm is proposed for IEEE 802.11ah networks to jointly optimise uplink communications energy efficiency and delay via adaptive RAW duration and internal slot interval based on different group sizes and application types.

Chapter 5

Harvested-energy Powered Access Control

This chapter focuses on the channel access in energy harvesting networks, and a harvested-energy powered access control is proposed to improve the energy efficiency and achievable data rate for IEEE 802.11ah networks, in which the devices are equipped with an energy harvester and an energy storage. Section 5.1 presents the motivation of channel access control in harvested-energy powered networks. Section 5.2 proposes a harvested-energy powered energy-aware access window algorithm to improve energy efficiency by setting adaptive window size based on the energy availability and group sizes. Section 5.3 presents a harvested-energy powered energy-aware access window with grouping strategy algorithm to cluster highly dense devices and adapt window size to realise achievable data rate as well as improve energy efficiency.

5.1 Motivation

Energy harvesting technique has brought the possible solution for remote sensors to extract energy from ambient environment. However, these energy-harvesting devices

pose new challenges because of the uncertain amount of energy that is harvested from the environment [SK11][GKAAZ17][AL17]. For IEEE 802.11ah energy-harvesting devices, they can only contend within the RAW when they have sufficient amount of harvested-energy. Therefore, the energy harvesting technology has changed the fundamental design principles for IEEE 802.11ah. In the following work, an algorithm is proposed to set adaptive window size in energy harvesting networks to optimise energy efficiency according to the group sizes, energy stored in devices and channel conditions. Based on that, a grouping strategy is presented to cluster highly dense energy-harvesting devices to achieve the required data rate and the optimal energy efficiency.

5.2 Harvested-energy Powered Energy-aware Access Window Algorithm

5.2.1 System Model

An IEEE 802.11ah based network is considered as one AP surrounded by 6000 devices. Each device is equipped with an energy harvester and an energy-storage device to store the harvested-energy. There are Nt devices within a group, and the related RAW contains M slots. At the initial stage, all devices have no energy. All the devices harvest energy for a period of time. Only if the stored-energy is higher than the threshold, it can contend for accessing the channel based on the operation defined in IEEE 802.11ah, otherwise it would fall in the doze mode.

5.2.1.1 RAW Operation

In IEEE 802.11ah uplink communications, the devices which have buffered data for the AP randomly select one of the uplink time slots in their allocated RAW and attempt to access the channel. The detailed access process via RAW is shown in Fig. 5.1.

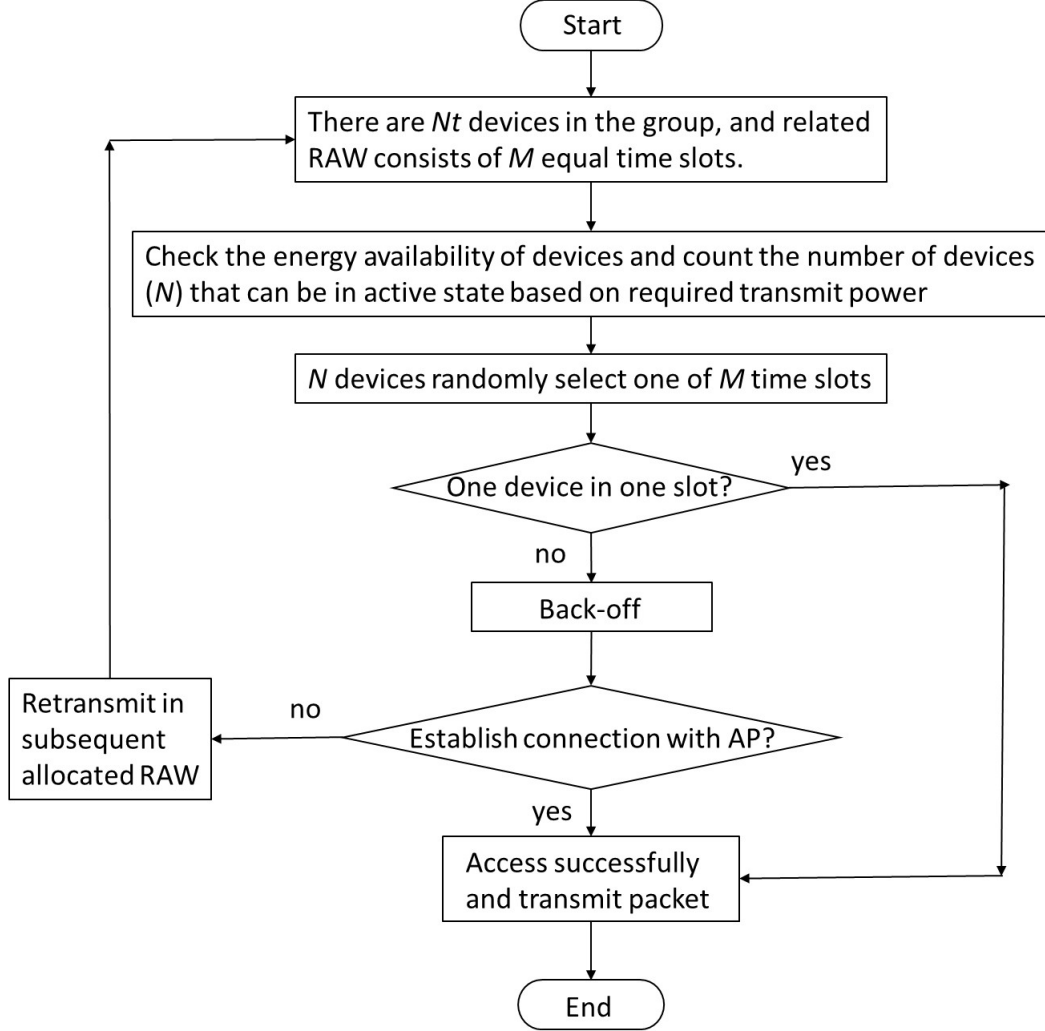


Fig. 5.1: Uplink channel access in IEEE 802.11ah with energy harvesting.

As an example shown in Fig. 5.2, after harvesting, only the device with enough energy can contend for channel access as Device 1, 2, 3, 4, $Nt(j) - 4$, $Nt(j) - 2$, $Nt(j) - 1$ and $Nt(j)$, while the Device $Nt(j) - 3$ enters doze mode since its stored energy is lower than the threshold. For all active devices, if there is only one device in a slot, it could access the channel without contention, for example, Devices 1 accesses in Slot 1 directly, and the same for Device 3 in Slot 5, Device $Nt(j) - 2$ in Slot $M(j)$, and Device $Nt(j)$ in Slot 3. When there are multiple devices choosing the same time slot, for example, Device 2, Device 4, Device $Nt(j) - 4$ and Device $Nt(j) - 1$ in Slot 2, they would go to the

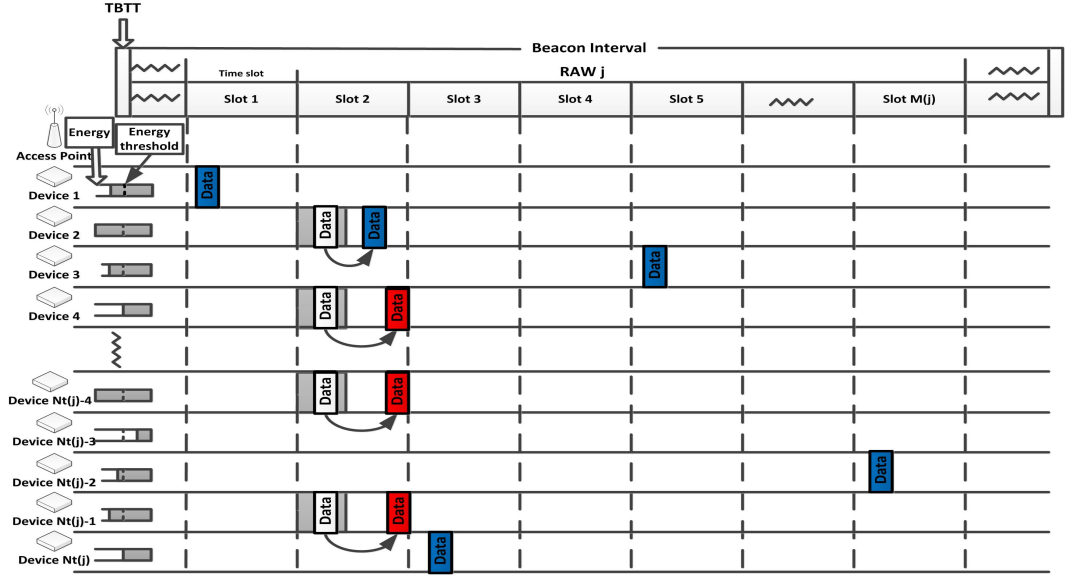


Fig. 5.2: Example of uplink RAW operation in IEEE 802.11ah with energy harvesting.

back-off stage to avoid collision by doubling the contention window and trying again until reaching the slot boundary. If accessing successfully, the device requests uplink communication by sending a PS-poll message to the AP. The AP responds with an ACK to confirm connection. After the first handshake, the device transmits its buffered data frame and waits for the ACK from the AP.

The process is repeated, one RAW by one RAW, until the end of the beacon frame as shown in Section 2.1.3 and Fig. 2.3.

5.2.1.2 Channel Condition

In the communication system, the budget is composed of all gains and losses due to distance, fading and shadowing [HRV12]. The principal link budget equation of the system is denoted by

$$\overline{P}_{RX} = \overline{P}_{TX} + G_{TX} - L_{TX} - PL(l) + G_{RX} - L_{RX}, \quad (5.1)$$

where \bar{P}_{RX} and \bar{P}_{TX} are the receiver and transmitter power; G_{TX} and G_{RX} are the antenna gains at the transmitter and receiver; L_{TX} and L_{RX} are the system losses at the transmitter and receiver; and $PL(l)$ is the path loss in dB at distance l .

The path loss of outdoor scenarios is based on the Macro Deployment or Pico/Hot Zone Deployment. When the antenna height is assumed 15m above rooftop and the path loss in dB is

$$PL(l) = 8 + 37.6 \log_{10}(l); \quad (5.2)$$

when the antenna height is assumed at rooftop level, the path loss is

$$PL(l) = 23.3 + 37.6 \log_{10}(l), \quad (5.3)$$

where l is in meter and the RF carrier frequency is assumed to be 900 MHz. For another frequency f , a correction factor of $21 \log_{10}(\frac{f}{900})$ should be added [HRV12][A⁺01].

5.2.2 Problem Formulation

In this section, the energy efficiency maximisation problem is derived based on the channel access via RAW for energy-harvesting devices in IEEE 802.11ah. The objective function is computed according to the number of available devices, window size and channel condition.

At the initial stage, all devices are equipped with the same energy level, equalling to 0, which can be denoted by $\bar{P}_g = 0$, where g is the index of devices. Then the devices would harvest the energy. At the end of the j th RAW, the energy of each device is

$$\bar{P}_{g-j} = \bar{P}_{g-(j-1)} + \bar{P}_{harvest-j} - \bar{P}_{consume-j}, \quad (5.4)$$

where $\bar{P}_{g-(j-1)}$ is the energy level at the end of $(j-1)th$ RAW; $\bar{P}_{harvest_j}$ is the harvested energy during the jth RAW, which is a random function as $\bar{P}_{harvest_j} = rate \times \eta$ where η is a random variable; $\bar{P}_{consume_j}$ is the energy consumption during jth RAW.

As for RAW, only the devices that store sufficient energy can contend, otherwise they fall into doze mode and wait for the subsequent allocated RAW. So the number of active devices can contend in the jth RAW is $N_j : \bar{P}_{g-(j-1)} > \varepsilon_{thr}$, where ε_{thr} is the threshold to guarantee the energy stored in the device is adequate to contend and access in one RAW in terms of distance, path loss, and achieved data rate. The state transition of devices is shown in Fig. 5.3. There are three states: State 1 (S1) is that the device stores enough energy and transmits successfully; State 2 (S2) is that although the device has enough energy, it does not succeed in accessing channel; State 3 (S3) is that the energy stored in device is not sufficient. Pe is the probability that a device store enough energy; Pj is the probability for a device to access channel successfully in the jth RAW.

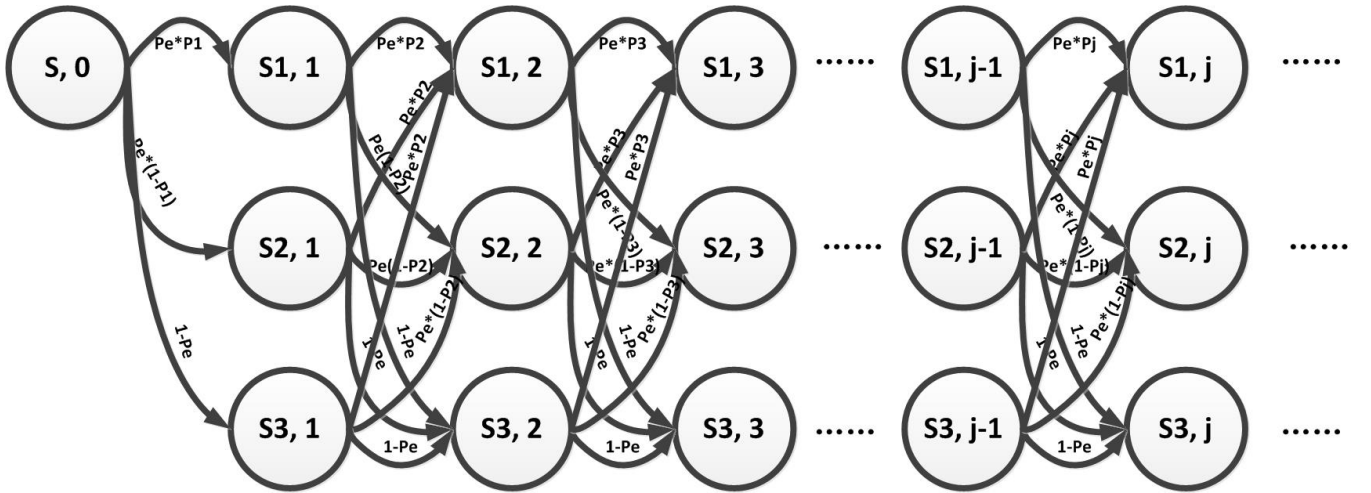


Fig. 5.3: State transition between adjacent RAWs.

According to [PHL14], there are two cases for a device succeeding in transmitting the

uplink data packet in energy harvesting networks.

- Case 1: the time slot is selected by only one device. Thus this device can occupy the whole slot to transmit packet directly without contention.
- Case 2: the time slot is selected by multiple devices. They would come into the back-off stage to avoid collision by doubling contention window. In addition, the collision does not occur if one of the devices could access the channel in the first back-off stage.

Case 1 is the state without contention as there is only one device in one slot after random selection. This device can transmit the packet directly. So the transmission probability for one device in Case 1 is that no other devices choose the slot that is selected by this device, denoted as

$$P_{j,1} = (1 - \frac{1}{M_j})^{N_j-1}, \quad (5.5)$$

where M_j is the number of active devices and N_j is the number of active devices.

Case 2 is the state with contention via back-off stage as when multiple devices selecting the same slot, the devices will go to the back-off stage and a collision does not occur if one of them will succeed in accessing the channel at the first back-off stage.

The probability for multiple (i and $i > 1$) devices to choose the same slot is

$$P_j(i) = \binom{N_j}{i} (\frac{1}{M_j})^i (1 - \frac{1}{M_j})^{N_j-i}. \quad (5.6)$$

So the probability of multiple devices to choose the same slot in the j th RAW is $P_j(i > 1) = \sum_{i=2}^{N(j)} P_j(i)$.

These i devices in one slot will go to the back-off stage. The probability for one

device to build connection with AP through the minimum contention window as the first back-off stage is obtained which alike that this device occupies the front slot without other devices, which is denoted as

$$P_{back-off}(i) = \sum_{x=0}^{W_{\min}-1} \left\{ \prod_0^x \left[1 - \frac{1}{W_{\min}} \left(1 - \frac{x}{W_{\min}} \right)^{i-1} \right] \right\} \frac{1}{W_{\min}} \left(1 - \frac{x+1}{W_{\min}} \right)^{i-1}, \quad (5.7)$$

where W_{\min} is the minimal size of contention window.

Hence, with i devices selecting the same time slot, a device can access the channel at the first back-off stage and communicate with AP with the probability of $P_j(i)P_{back-off}(i)$. So as i ranges from 2 to N , for the Case 2, the transmission probability is the sum of multiple devices in one slot as

$$P_{j,2} = \sum_{i=2}^N P_j(i)P_{back-off}(i). \quad (5.8)$$

The successful transmission probability for one device to transmit one packet in the j th RAW is the sum of two cases, which can be denoted by

$$P_j = P_{j,1} + P_{j,2}. \quad (5.9)$$

The energy consumption for a device to access channel is related to the required data rate, channel conditions, and the distance between devices and AP.

Based on Shannon Equation, the received power of a packet is evaluated with data rate and bandwidth as

$$\left(\frac{\bar{P}_{RX}}{\bar{N}} \right)_{dB} = \left(\frac{E_b}{N_0} \right)_{dB} + 10 \log_{10} \left(\frac{\bar{C}}{\bar{B}} \right), \quad (5.10)$$

where $\frac{E_b}{N_0}$ is the ratio of the required energy per bit to the noise power density; \overline{N} is the received noise power; \overline{N}_0 is the Thermal noise power density; \overline{C} is the bit rate and B is the bandwidth.

The received noise power can be denoted as

$$\overline{N} = \overline{N}_0 B = k_b T_0 F B, \quad (5.11)$$

where k_b is the Boltzmann's constant (Joule/Kelvin); T_0 is the receiver temperature in Kelvins (typically set as 293 K) and F is the receiver noise figure.

To obtain $\frac{E_b}{N_0}$, the bit error rate needs to be considered. The relationship between packet error rate and bit error rate is

$$PER = 1 - (1 - BER)^\gamma, \quad (5.12)$$

where PER is the packet error rate, while BER is the bit error rate. γ is the packet size in bit [HRV12].

In Additive White Gaussian Noise (AWGN) channel, the bit error rate can be denoted as

$$BER = Q\left(\sqrt{\frac{2E_b}{\overline{N}_0}}\right). \quad (5.13)$$

According to the link budget, the overall gain due to the channel is

$$(G)_{dB} = G_{TX} - L_{TX} - PL(l) - FM + G_{RX} - L_{RX}, \quad (5.14)$$

where FM is the fade margin.

So Equation 5.10 can be transformed to

$$\left(\frac{\bar{P}_{TX}(l)G}{k_b T_0 F B}\right)_{dB} = \left(\frac{E_b}{N_0}\right)_{dB} + \left(\frac{\bar{C}}{B}\right)_{dB}. \quad (5.15)$$

For Binary Phase Shift Keying (BPSK) modulation, the $\left(\frac{E_b}{N_0}\right)_{dB}$ in AWGN channel is 9dB when PER is 10% and 1024 bits per packet.

The energy consumption for a device to access channel and transmit a packet in one RAW is estimated based on different states that a device may fall into with various probability, which is denoted by

$$E_{j,t} = P_{j,1}\bar{P}_{TX}(l) + P_{j,2}2\bar{P}_{TX}(l) + (1 - P_j)2.5\bar{P}_{TX}(l) + M_j\tau E_{wake-up}, \quad (5.16)$$

where l is the distance between a device and AP; $(1 - P_j)$ is the probability for one device fall into the collided state in j th RAW; $E_{wake-up}$ is the wake-up energy for a device in a unit time interval, which is the consumed energy to support the device in the wake-up mode and τ is the time duration of one uplink slot.

Thus, the energy threshold for device to access channel is

$$\varepsilon_{thr} = a + 3\bar{P}_{TX}, \quad (5.17)$$

where a is a constant.

The size of RAW also has the impact on the energy consumption of transmitting signalling information, because for a short RAW duration, the signalling information of AP to each device will be high due to the scheduling information that needs to be transmitted multiple times in a short time. In addition, if the group size is small, it also needs massive scheduling information to realise network communications. So the energy

consumption of signalling information is related to N_j and M_j :

$$E_{j_signal} = \frac{\alpha}{M_j} \times \frac{\beta}{N_j}, \quad (5.18)$$

where α is the parameter indicating the traffic and β is related to the overall number of devices in this scenario.

The overall energy consumption for a group of devices to access within one RAW consists of transmission energy and signalling energy, which is denoted by

$$E_{j_overall} = N_j P_{consume_j} = N_j (E_{j_t} + E_{j_sigal}). \quad (5.19)$$

Throughput for a RAW is the ratio of number of bits that can be transmitted in one RAW to the RAW duration, which is formulated as

$$R_j = \frac{N_j \times P_j \times \gamma}{\tau M_j}. \quad (5.20)$$

Energy efficiency for one RAW is evaluated by the throughput it provides and the overall energy consumption including transmitting energy and signalling energy.

Thus the optimisation problem is formulated as

$$\begin{aligned} \max. \quad & EE(M_j, N_j) = \frac{R_j}{E_{j_overall}}, \\ \text{s.t.} \quad & N_j = \text{count } g, \text{ where } \bar{P}_{g-(j-1)} > \varepsilon_{thr}. \end{aligned} \quad (5.21)$$

5.2.3 Harvested-energy Powered Energy-aware Access Window

In this section, a harvested-energy powered energy-aware access window algorithm is proposed to optimise energy efficiency for uplink harvested-energy powered IEEE 802.11ah

communications.

The main part $f(M_j)$ of uplink energy efficiency along with the various number of time slots in one uplink RAW (M_j) can be denoted by

$$f(M_j) = \frac{P_j}{M_j \tau [E_{j,t} + E_{j_signal}]}. \quad (5.22)$$

Since $P_{j,1}$ and $P_{j,2}$ could be regarded as binomial distribution, when N_j is large (i.e., $N_j \geq 20$), the expressions for the probability of both cases can be approximated by the Poisson distribution:

$$P_{j,1} = N_j e^{-\frac{N_j}{M_j}}, \quad (5.23)$$

$$P_{j,2} = \sum_2^{N_j} P_{back-off}(i) \frac{\left(\frac{N_j}{M_j}\right)^i e^{-\frac{N_j}{M_j}}}{i!}. \quad (5.24)$$

One of the main factors to indicate concavity and convexity characteristics of a function is the second order derivation. Based on the Poisson distribution, the result of the second order derivation of $f(M_j)$ can be expressed as

$$f''(M_j) = \frac{e^{\frac{-N_j}{M_j}} N_j^2 \ln e (N_j \ln e - 2M_j) (\tau M_j^5)^{-1}}{2.5 \bar{P}_{TX} - 1.5 N_j \bar{P}_{TX} e^{\frac{-N_j}{M_j}} + \tau E_{wake-up} M_j}, \quad (5.25)$$

which is negative as $(N_j \ln e - 2M_j) < 0$ and $2.5 \bar{P}_{TX} - 1.5 N_j \bar{P}_{TX} e^{\frac{-N_j}{M_j}} > 0$, indicating it is a concave curve with one maximum point along with different uplink RAW sizes.

The optimal RAW size is found based on different number of available devices to maximise energy efficiency by applying Gradient Descent as shown in Algorithm 8.

Algorithm 8 is a standard Gradient Descent approach to find the optimal solution,

Algorithm 8 Gradient Descent Harvested-energy Powered Energy-aware Access Window Algorithm

- 1: **Initialisation: zero energy is assigned to the devices in networks.**
 - 2: Each device harvests energy and stores the energy to the Energy Storage.
 - 3: **Step 1: AP identifies the number of devices per group N_j , and sets access threshold based on transmit power.**
 - 4: $(\frac{\bar{P}_{TX}(l)G}{k_b T_0 F B})_{dB} = (\frac{E_b}{N_0})_{dB} + (\frac{C}{B})_{dB}$
 - 5: $\varepsilon_{thr} = a + 3\bar{P}_{TX}$
 - 6: $N_j = \text{count } g, \text{ where } \bar{P}_{g.(j-1)} > \varepsilon_{thr}$
 - 7: **Step 2: Estimate the optimal uplink RAW size for a certain group.**
 - 8: **loop**
 - 9: Initialise M_{j_old} and M_{j_new} as two random numbers.
 - 10: $EE'(M_j) = \frac{\partial(-EE(M_j, N_j))}{\partial M_j}$
 - 11: **while** $|EE(M_{j_old}) - EE(M_{j_new})| \geq \text{precision}$ **do**
 - 12: $\partial = 0.01$
 - 13: $M_{j_old} = M_{j_new}$
 - 14: $M_{j_new} = M_{j_old} - \partial \times EE'(M_j)$
 - 15: **end while**
 - 16: return M_j
 - 17: **end loop**
 - 18: **Step 3: AP sets the window size as M_j equal time slots. The devices in this group fall into sleep mode and wake up until coming to their allocated window.**
 - 19: **Step 5: N_j devices in the group try to establish connection with AP by randomly selecting one of M_j time slots in RAW and attempt to access the channel.**
 - 20: N_j devices in the group choose one of M_j slots randomly.
 - 21: Devices attempt to access channel to establish connection with AP as Case 1 and Case 2. When only one device in one slot, the device accesses channel directly without contention; when multiple devices in one slot, the devices contend and attempt to access medium via the back-off stage.
 - 22: When the device can not access in its slot, re-attempt in the next allocated window.
-

which is a method requiring small working and storage space. It begins with an initial value and finds the optimal value according to the gradient descent route.

5.2.4 Simulation Results

In this section, the proposed algorithm for RAW is evaluated in Matlab. An outdoor IEEE 802.11ah network as one AP with 6000 devices is considered, where the antenna height is 15m above rooftop. The devices are randomly clustered into several groups.

Each group is assigned to a RAW to access channel. The optimal value is found based on the setting of 200 to α and β respectively. The simulation is done for a certain time to evaluate the energy efficiency and packet delivery ratio. The main simulation parameters are given in Table 5-A.

Table 5-A: Simulation Parameters for Harvested-energy Powered Energy-aware Access Window in IEEE 802.11ah Uplink Communications

Parameter	Value	Parameter	Value
Frequency	0.9 GHz	Data rate	100 kbps
$G_TX(dBm)$	0	$G_RX(dBm)$	3
Noise figure (dB)	3	Fade Margin (dB)	10.3
Modulation	BPSK	PER	10%
Bandwidth	2 MHz	Idle listening power	0.001 mw
Slot duration	31.1 ms	Packet size	1024 bits
Min contention window	8	Max contention window	1024

Fig. 5.4 shows the uplink energy efficiency analysis with different group sizes. It can be observed that along with different group scales, the uplink energy efficiency of the

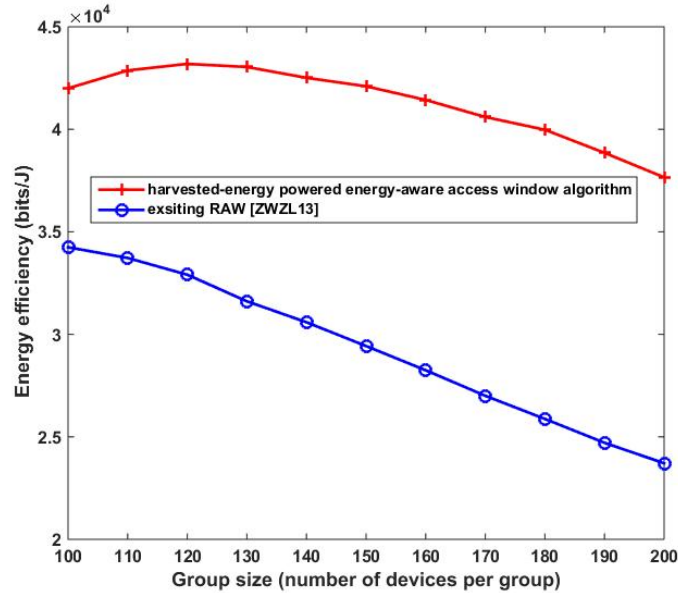


Fig. 5.4: Energy efficiency comparison per RAW with different group sizes between harvested-energy powered energy-aware access window and existing window in [ZWZL13].

proposed algorithm is in general 37.5% higher than the compared existing RAW control in [ZWZL13]. For the existing window, the contention level increases as the group size grows, thus the curve of existing window goes down along the increment of group sizes. With the increasing number of devices per group, the energy efficiency of the proposed algorithm goes up since more devices would lead to more available devices per group for a higher throughput. But after the peak, the curve declines. High number of devices would increase the contention, which composes the reason for lower energy efficiency. In order to alleviate the contention, the number of time slots of the proposed algorithm would increase when more devices attempt to access in one group, which enlarges the wake-up power (another factor to reduce energy efficiency). The larger RAW size is also the reason for more distinct improvement with enlarging the group size, since comparing with the static RAW, there are more options in the proposed algorithm for devices to choose, so the collision probability and the signalling energy consumption would be lower than the exiting one.

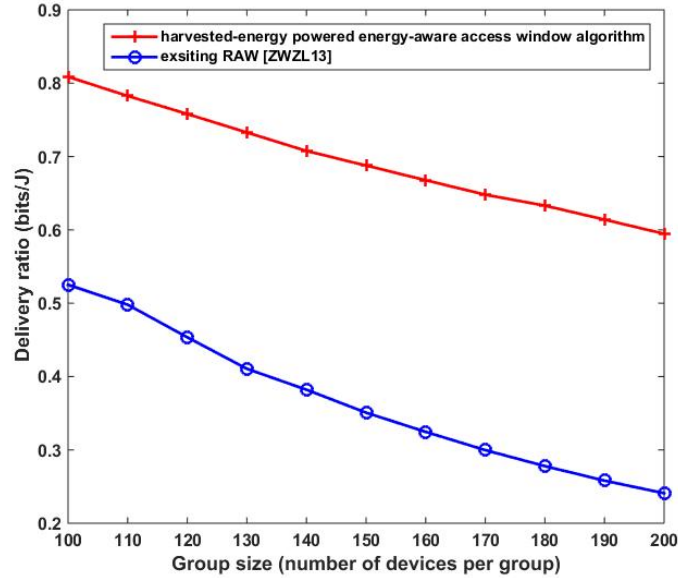


Fig. 5.5: Packet delivery ratio comparison per RAW with different group sizes between harvested-energy powered energy-aware access window and existing window in [ZWZL13].

Fig. 5.5 shows the delivery ratio along with different group sizes. The delivery ratio of the proposed algorithm is in general 75% higher than the existing RAW in [ZWZL13]. For more devices in one group, the contention level would increase, thus the delivery ratio goes down. The RAW size is determined by the number of devices in the proposed algorithm, so in the circumstance that there are more devices in one group, the related RAW contains more time slots to alleviate contention and improve delivery ratio.

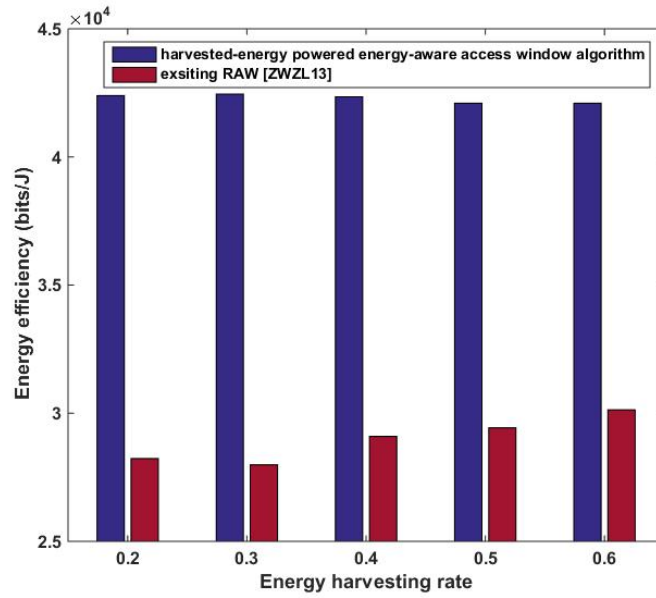


Fig. 5.6: Energy efficiency per RAW with different energy harvesting rates between harvested-energy powered energy-aware access window and existing window in [ZWZL13].

Fig. 5.6 shows the energy efficiency along with different harvesting rates for 150 devices per group. The proposed algorithm outperforms the existing window in [ZWZL13] with general 57.4% improvement. As the increment of harvesting rate, the number of active devices and the energy stored in devices would increase. Thus, the energy efficiencies for two controls are going up because of higher throughput. For the proposed algorithm, as it sets the adaptive window according to the number of available devices, the energy consumption for devices is lower than the existing window. However, if the number of available devices is too large under the high harvesting rate, the contention level would be higher, so the energy efficiency would decrease.

5.3 Harvested-energy Powered Energy-aware Access Window with Grouping Strategy Algorithm

5.3.1 System Model

An IEEE 802.11ah network as a single AP surrounded by 6000 devices is considered. Each device is equipped with an energy harvester and an energy-storage device to store the harvested-energy. AP groups the devices and assigns a RAW to each group. The limitation of the number of devices in one group is σ . There are N ($N \leq \sigma$) devices within a group, and the related RAW contains M slots. At the initial stage, all devices have no energy. All the devices harvest energy for a period of time. The devices which store enough energy would be clustered, while other devices would fall into doze state to continue to harvest energy, illustrated as shown in Fig. 5.7.

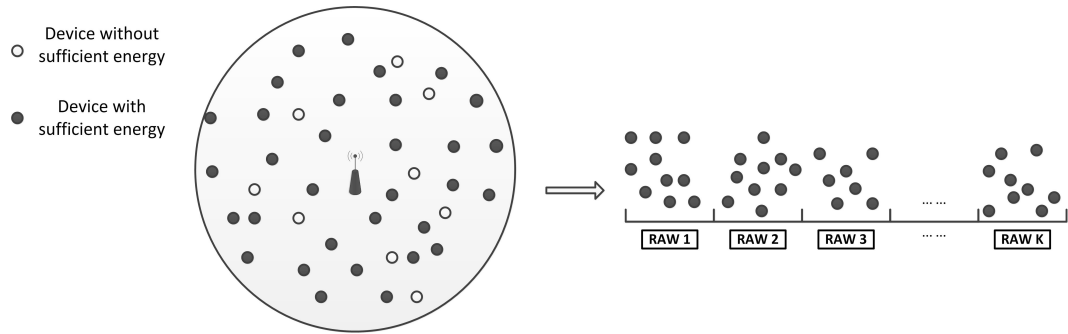


Fig. 5.7: System model.

5.3.1.1 RAW operation

In IEEE 802.11ah uplink communications, the devices which have buffered data for the AP randomly select one of the uplink time slots in their allocated RAW and attempt to access the channel. The detailed access process via RAW is shown in Fig. 5.8.

As an example shown in Fig. 5.9, after harvesting, only the device with enough

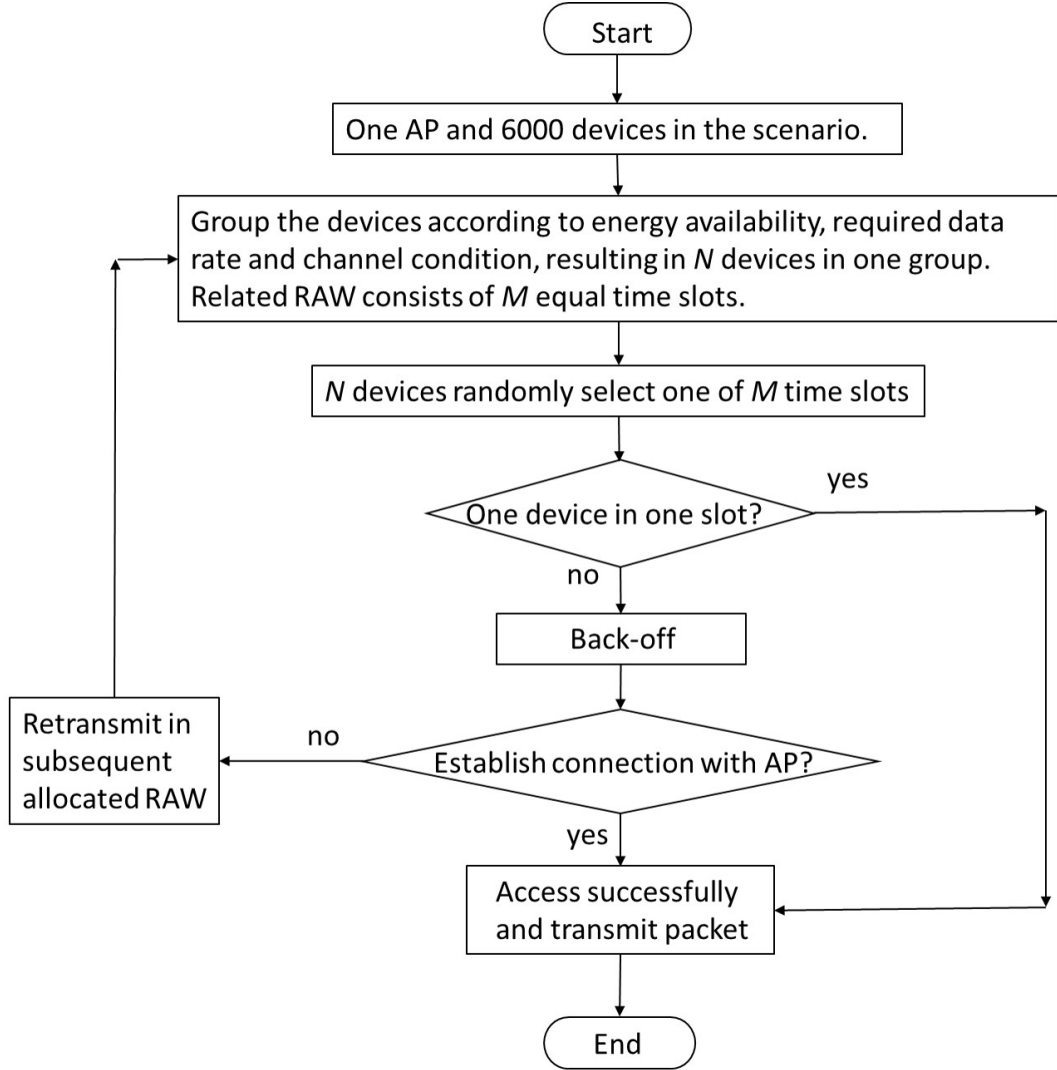


Fig. 5.8: Uplink operation of RAW with group strategy and energy harvesting.

energy for the required data rate can be grouped to attempt to access the channel. The operation of channel access is the same as Chapter 3 because the grouped devices are all with sufficient energy. After random selection, if there is only one device choosing a slot, it can access the channel directly, for instance, Device 1 transmits the packet without contention in Slot 1, and the same for Devices 3 in Slot 5, Device $N(j) - 3$ in Slot 4, Device $N(j) - 2$ in Slot $M(j)$, and Device $N(j)$ in Slot 3. When there are more than one devices choosing the same time slot, for instance, Device 2, Device 4, Device $N(j) - 4$ and Device $N(j) - 1$ in Slot 2, they would enter the back-off stage (signed as grey

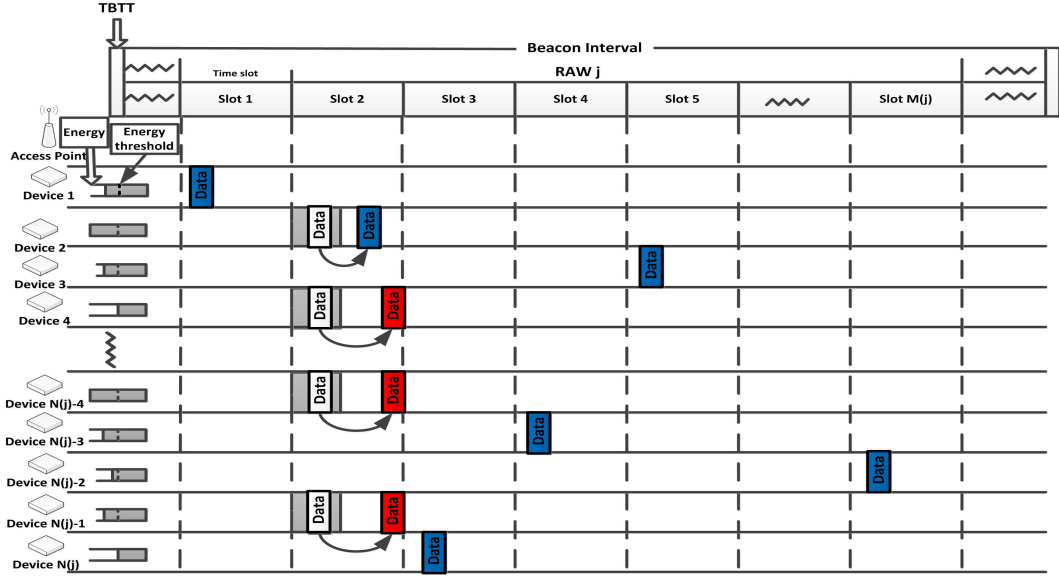


Fig. 5.9: Example of uplink RAW operation in IEEE 802.11ah with group strategy and energy harvesting.

in Fig. 5.9) to avoid collision by doubling contention window and trying again until reaching the slot boundary. Device 2 accesses the channel successfully at the back-off stage, so Device 2 transmits uplink data to the AP, while Device 4, Device $N(j) - 4$ and Device $N(j) - 1$ need to re-transmit in the subsequent allocated window. If accessing the channel successfully, device requests uplink communications by sending a PS-poll message to the AP. The AP responds with an ACK to confirm the connection. After the first handshake, the device transmits the buffered uplink data frame and waits for the ACK from the AP after a SIFS period [Par13].

The process is repeated, one RAW by one RAW, until the end of the beacon frame as shown in Section 2.1.3 and Fig. 2.3.

5.3.1.2 Channel Condition

In the communication system, the budget is composed of all gains and losses due to distance, fading and shadowing [HRV12]. The main principal link budget equation of

the system is denoted by

$$\bar{P}_{RX} = \bar{P}_{TX} + G_{TX} - L_{TX} - PL(l) + G_{RX} - L_{RX}, \quad (5.26)$$

where \bar{P}_{RX} and \bar{P}_{TX} are the receiver and transmitter power; G_{TX} and G_{RX} are the antenna gains at the transmitter and receiver; L_{TX} and L_{RX} are the system losses at the transmitter and receiver; and $PL(l)$ is the path loss in dB at distance l .

The path loss of outdoor scenarios is based on the Macro Deployment or Pico/Hot Zone Deployment. When the antenna height is assumed to be 15m above rooftop and the path loss in dB is

$$PL(l) = 8 + 37.6 \log_{10}(l); \quad (5.27)$$

when the antenna height is assumed at rooftop level, the path loss is

$$PL(l) = 23.3 + 37.6 \log_{10}(l), \quad (5.28)$$

where l is in meter and the RF carrier frequency is assumed to be 900 MHz. For another frequency f , a correction factor of $21 \log_{10}(\frac{f}{900})$ should be added [HRV12][A⁺01].

5.3.2 Problem Formulation

In this section, the uplink energy efficiency maximisation problem is derived according to the grouping strategy and channel access process.

5.3.2.1 Grouping strategy

At the initial stage, all devices are equipped with the same energy level, equalling to 0, which can be denoted by $\bar{P}_g = 0$, where g is the index of devices. Then the devices

would harvest the energy. At the end of the j th RAW, the energy of each device is

$$\bar{P}_{g-j} = \bar{P}_{g-(j-1)} + \bar{P}_{harvest-j} - \bar{P}_{consume-j}, \quad (5.29)$$

where $\bar{P}_{g-(j-1)}$ is the energy level at the end of $(j-1)$ th RAW; $\bar{P}_{harvest-j}$ is the energy harvested during j th RAW, which is a random function as $\bar{P}_{harvest-j} = rate \times \eta$ where η is a random variable; $\bar{P}_{consume-j}$ is the energy consumption during j th RAW.

Based on Shannon Equation, the received power of a packet is evaluated with data rate and bandwidth as

$$\left(\frac{\bar{P}_{RX}}{\bar{N}}\right)_{dB} = \left(\frac{E_b}{N_0}\right)_{dB} + 10\log_{10}\left(\frac{\bar{C}}{B}\right), \quad (5.30)$$

where $\frac{E_b}{N_0}$ is the ratio of required energy per bit to the noise power density; \bar{N} is the received noise power; N_0 is the Thermal noise power density; \bar{C} is the bit rate and B is the bandwidth.

The received noise power can be denoted as

$$\bar{N} = N_0 B = k_b T_0 F B, \quad (5.31)$$

where k_b is the Boltzmann's constant (Joule/Kelvin); T_0 is the receiver temperature in Kelvins (typically set as 293 K) and F is the receiver noise figure.

To obtain $\frac{E_b}{N_0}$, the bit error rate needs to be considered. The relationship between packet error rate and bit error rate is

$$PER = 1 - (1 - BER)^\gamma, \quad (5.32)$$

where PER is the packet error rate, while BER is the bit error rate. γ is the packet size in bit [HRV12].

In AWGN channel, bit error rate can be denoted as

$$BER = Q\left(\sqrt{\frac{2E_b}{N_0}}\right). \quad (5.33)$$

According to the link budget, the overall gain due to the channel is

$$(G)_{dB} = G_{TX} - L_{TX} - PL(l) - FM + G_{RX} - L_{RX}, \quad (5.34)$$

where FM is the fade margin.

So Equation 5.30 can be transformed to

$$\left(\frac{\bar{P}_{TX}(l)G}{k_b T_0 F B}\right)_{dB} = \left(\frac{E_b}{N_0}\right)_{dB} + \left(\frac{\bar{C}}{B}\right)_{dB}. \quad (5.35)$$

For BPSK modulation, the $\left(\frac{E_b}{N_0}\right)_{dB}$ in AWGN channel is 9dB when PER is 10% and 1024 bits per packet.

As for RAW, only the devices that have sufficient energy could contend, otherwise they fall into the doze mode and wait for another RAW. So one factor is defined to show the energy level of devices as

$$\xi = \frac{\bar{P}_{g-(j-1)} - \varepsilon_{thr}}{\varepsilon_{thr}}, \quad (5.36)$$

where ε_{thr} is the threshold to guarantee the energy stored in the device is adequate to contend and communicate in one RAW in terms of distance, pass loss, and the required data rate.

The threshold for accessing is denoted as

$$\varepsilon_{thr} = a + 3\bar{P}_{TX} \quad (5.37)$$

where a is a constant.

So the devices with the highest ξ are grouped to attempt to access via RAW as

$$Group_j = \{Device(\xi_{\max})\}, \quad (5.38)$$

where the number of devices in this group should be less than the limitation of group size as $N_j = |Group_j| < \sigma$ (σ is the group size limitation).

5.3.2.2 Energy efficiency

Energy efficiency is evaluated in the same way as the formulation in Section 5.2. It is the ratio of the throughput it provides to the overall energy consumption to show the number of bits could be transmitted by consuming a certain amount of energy. The throughput for accessing channel is the number of bits that can be transmitted in one window.

So the throughput for one uplink RAW is

$$R_j = \frac{N_j \times P_j \times \gamma}{\tau M_j}, \quad (5.39)$$

where γ is the number of bits in one uplink packet. $N_j \times P_j \times \gamma$ is the total length of packets that could be transmitted for a group with N_j devices within M_j time slots. τM_j is the total time of one uplink RAW.

The overall energy consumption for one device consists of accessing power and over-

head power during uplink RAW, which can be formulated as

$$E_{j_overall} = N_j(E_j + E_{j_signal}). \quad (5.40)$$

Energy efficiency is a main parameter to show efficiency of energy utilisation. Thus the energy efficiency for the j th window is

$$EE_j(M_j, N_j) = \frac{R_j}{E_{j_overall}} = \frac{\gamma P_j}{\tau M_j(E_j + E_{j_signal})}. \quad (5.41)$$

For P_j , E_j and E_{j_signal} built by N_j and M_j , uplink energy efficiency is a function related to the number of devices in one group, and the number of time slots in the related window for the group for one IEEE 802.11ah based network.

5.3.3 Harvested-energy Powered Energy-aware Access Window with Grouping Strategy

In this section, an harvested-energy powered energy-aware access window with grouping strategy algorithm is proposed to optimise the energy efficiency for uplink IEEE 802.11ah communications.

The main part $f(M_j)$ of uplink energy efficiency along with the various number of time slots in one uplink RAW (M_j) can be denoted by

$$f(M_j) = \frac{P_j}{M_j \tau [E_j + E_{j_signal}]}. \quad (5.42)$$

Since P_{j_1} and P_{j_2} could be regarded as binomial distribution, when N_j is large (i.e., $N_j \geq 20$), the expressions for the probability of both cases can be approximated by the

Poisson distribution:

$$P_{j.1} = N_j e^{-\frac{N_j}{M_j}}, \quad (5.43)$$

$$P_{j.2} = \sum_2^{N_j} P_{back-off}(i) \frac{\left(\frac{N_j}{M_j}\right)^i e^{-\frac{N_j}{M_j}}}{i!}. \quad (5.44)$$

So based on the Poisson distribution, the $f(M_j)$ can be expressed as

$$f(M_j) = \frac{N_j e^{-\frac{N_j}{M_j}} \tau^{-1}}{(M_j)^2 \tau E_{wake-up} - 1.5 M_j N_j \bar{P}_{TX} e^{-\frac{N_j}{M_j}} + M_j 2.5 \bar{P}_{TX}}. \quad (5.45)$$

One of the main factors to indicate concavity and convexity of a function is the second order derivation. Through calculation, the result of the second order derivation of $f(M_j)$ could be simplified as

$$f''(M_j) = \frac{e^{\frac{-N_j}{M_j}} N_j^2 \ln e (N_j \ln e - 2M_j) (\tau M_j^4)^{-1}}{2.5 \bar{P}_{TX} M_j - 1.5 M_j N_j \bar{P}_{TX} e^{\frac{-N_j}{M_j}} + \tau E_{wake-up} (M_j)^2}, \quad (5.46)$$

which is negative as $(N_j \ln e - 2M_j) < 0$ and $2.5 \bar{P}_{TX} M_j - 1.5 M_j N_j \bar{P}_{TX} e^{\frac{-N_j}{M_j}} > 0$, indicating it is a concave curve with one maximum point along different uplink RAW duration.

The optimal RAW duration based on grouping results is found for uplink communications to optimise energy efficiency by applying Gradient Descent approach, a fast algorithm to find the optimum of large search space as shown in Algorithm 9.

This algorithm is a standard Gradient Descent approach to find the optimal solution based on the grouping strategy. The devices are clustered based on the grouping strategy first. And the random window size is given to the optimal problem. And then the input takes steps proportional to the positive of the gradient. The optimal window size M is the one when the gap between subsequent outcomes are below the threshold. After that, the grouped devices attempt to access channel via the optimal window size.

Algorithm 9 Gradient Descent Harvested-energy Powered Energy-aware Access Window with Grouping Strategy Algorithm

- 1: **Initialisation: zero energy is assigned to the devices in networks.**
 - 2: Each device harvests energy and stores the energy to Energy Storage.
 - 3: **Step 1: AP groups the devices with the highest ξ .**
 - 4: Transmit power is determined according to the packet error rate, signal modulation mode, distance between device and AP, required data rate and bandwidth.
 - 5: $(\frac{\bar{P}_{TX}(l)G}{k_b T_0 F B})_{dB} = (\frac{E_b}{N_0})_{dB} + (\frac{\bar{C}}{B})_{dB}$.
 - 6: Set the factor ξ as $\xi = \frac{\bar{P}_{g-(j-1)} - \varepsilon_{thr}}{\varepsilon_{thr}}$ where $\varepsilon_{thr} = a + 3 \times \bar{P}_{TX}$.
 - 7: The devices with the highest ξ are clustered.
 - 8: **while** $N_j < \sigma$ **do**
 - 9: $Device(\xi_{\max}) \Rightarrow Group_j$
 - 10: $N_j = N_j + 1$
 - 11: **end while**
 - 12: **Step 2: Estimate the optimal uplink RAW size for a certain group.**
 - 13: **loop**
 - 14: Initialise $M_{j_{old}}$ and $M_{j_{new}}$ as two random numbers.
 - 15: $EE'(M_j) = \frac{\partial(-EE(M_j, N_j))}{\partial M_j}$
 - 16: **while** $|EE(M_{j_{old}}) - EE(M_{j_{new}})| \geq precision$ **do**
 - 17: $\partial = 0.01$
 - 18: $M_{j_{old}} = M_{j_{new}}$
 - 19: $M_{j_{new}} = M_{j_{old}} - \partial \times EE'(M_j)$
 - 20: **end while**
 - 21: return M_j
 - 22: **end loop**
 - 23: **Step 3: AP sets the window size as M_j equal time slots for j th group. The devices in this group fall into sleep mode and wake up until coming to their allocated window.**
 - 24: **Step 4: N_j devices in the group try to establish connection with AP by randomly selecting one of M_j time slots in RAW and attempt to access the channel.**
 - 25: N_j devices in the group choose one of M_j slots randomly.
 - 26: Devices attempt to access channel to establish connection with AP as Case 1 and Case 2.
 - 27: When the device could not access in its slot, re-attempt in the next allocated window.
-

5.3.4 Simulation Results

In this section, the proposed algorithm for RAW is evaluated in Matlab. An outdoor IEEE 802.11ah network as one AP with 6000 devices is considered, where antenna height is 15m above rooftop. The nodes in the scenario are following normal distribution, which means more devices close to AP and less devices in the boundary of scenario. Each group

is assigned to a RAW to access channel. The optimal value is found based on the setting of 200 to α and β respectively. Each participated device has exactly one packet to transmit for uplink communications respectively during a RAW. The uplink energy efficiency for IEEE 802.11ah based networks is simulated under various number of devices per group and different device distributions. The main simulation parameters are given in Table 5-B.

Table 5-B: Simulation Parameters for Harvested-energy Powered Energy-aware Access Window with Grouping Strategy in IEEE 802.11ah Uplink Communications

Parameter	Value	Parameter	Value
Frequency	0.9 GHz	Data rate	100 kbps
$G_TX(dBm)$	0	$G_RX(dBm)$	3
Noise figure (dB)	3	Fade Margin (dB)	10.3
Modulation	BPSK	PER	10%
Bandwidth	2 MHz	Idle listening power	0.001 mw
Packet size	1024 bits	Time slot duration	31.1 ms
Min contention window	8	Max contention window	1024

Fig. 5.10 shows the energy efficiency comparison varying over diverse group size limitations (maximum number of devices per group) for each group. The existing window size is fixed as 100 slots per window [ZWZL13], and the existing clustering is random grouping. The proposed window improves around 52.9% and 317% than the fixed window with proposed grouping strategy and the existing one respectively. The curves of the proposed and fixed window with grouping strategy under two energy harvesting rates are all concave with one peak point, while the existing one is going up as the number of available devices increases along the group size and the harvesting rate. The peak point of fixed window with grouping strategy is located at maximal 90 devices per group, while that of proposed algorithm are at 150 and 140 for rate=0.2 and 0.5 respectively. The proposed window size is set based on the group size and the position of devices, thus a larger window is provided to a big group which is far from the AP, so that the

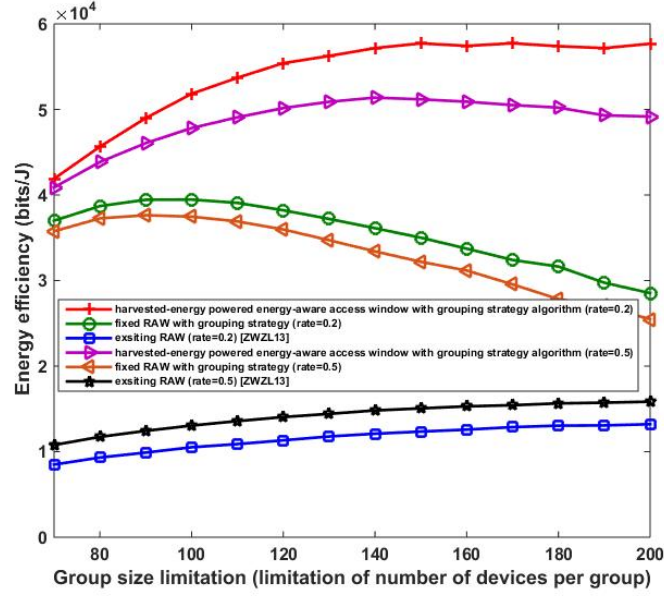


Fig. 5.10: Energy efficiency comparison per RAW with different group size limitations among harvested-energy powered energy-aware access window with grouping strategy, fixed RAW with grouping strategy and existing window in [ZWZL13].

energy efficiency is higher. For a high harvesting rate, the devices that far from the AP can store sufficient energy to access the channel, however, in such condition, the energy consumption would be large as higher transmit power is required to realise the expected data rate, which is a factor for lower energy efficiency.

With low limitation of group size, the signalling energy consumption would be high to achieve the whole network communications since scheduling information would be sent multiple times after a short time to achieve the whole network communications. So with the increment of group size limitation, the signalling energy consumption would decrease, which is a dominant factor to increase the energy efficiency. However, with large group size limitation, the collision probability would be high due to the high contention, which leads to consuming more energy and reducing the throughput (two parameters for low efficiency), thus the trend of curves will go down.

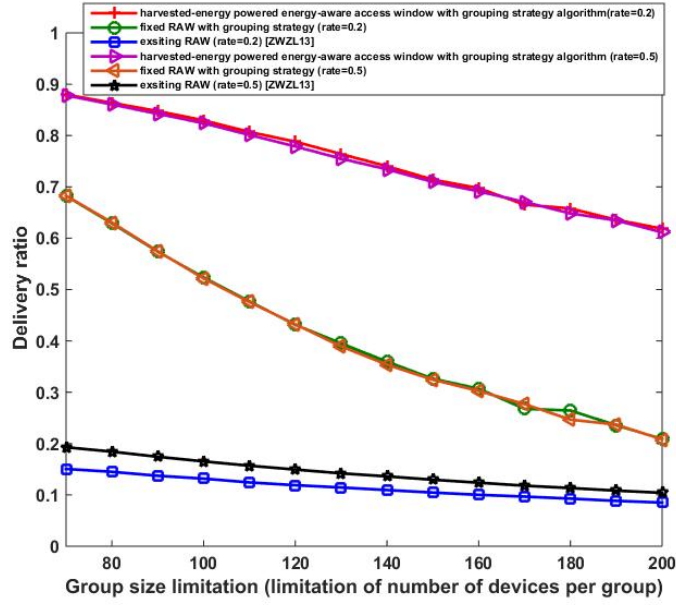


Fig. 5.11: Packet delivery ratio comparison per RAW with different group size limitations among harvested-energy powered energy-aware access window with grouping strategy, fixed RAW with grouping strategy and existing window in [ZWZL13].

Fig. 5.11 shows the delivery ratio comparison varying over diverse group size limitations. The proposed window outperforms the fixed window with grouping strategy and the existing window in [ZWZL13] with 87.5% and 317% improvement respectively. The packet delivery ratio goes down with the increment of group size limitation, as the contention is higher for a group with more devices so that the collision probability would increase. The window size of the proposed window is larger for a large group, which could alleviate the collision probability, thus the rate of decreasing for the proposed window is lower than the existing window. For different harvesting rates, the performance is the same as the rate has the influence on the energy consumption while it has few effect on the delivery ratio.

Fig. 5.12 shows the average distance of accessed devices varying along with different group size limitations. The average distance is larger for a high harvesting rate, as more transmit power is needed for the devices located at far side of the scenario and high

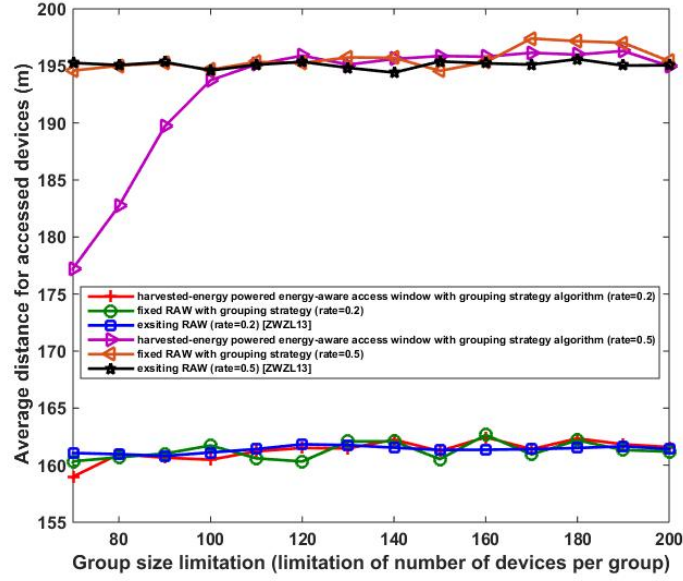


Fig. 5.12: Average distance of accessing devices comparison per RAW with different group size limitations among harvested-energy powered energy-aware access window with grouping strategy, fixed RAW with grouping strategy and existing window in [ZWZL13].

harvesting rate provides sufficient energy for these devices. In addition, the proposed adaptive window could provide dynamic window for different group sizes and locations, thus its capacity for the devices far away from the AP is larger than the existing window.

Simulation results demonstrate the proposed algorithm can bring superior energy efficiency and delivery ratio for IEEE 802.11ah uplink communications.

5.4 Summary

In this chapter, the harvested-energy powered access control is proposed to improve the energy efficiency in IEEE 802.11ah based energy harvesting networks, in which the devices are equipped with an energy harvester and an storage device. The energy efficiency optimisation problem is formulated by probability theory to monitor the access process taking into consideration of energy availability. In addition the energy con-

sumption is evaluated for various accessing states and channel conditions as the distance between device and AP, data rate and modulation mode. Then, the overall energy consumption and throughput are estimated to contribute to the energy efficiency.

The harvested-energy powered energy-aware access window algorithm is proposed to optimise the uplink energy efficiency by setting RAW duration for different group sizes and group distances with AP. Based on that, the harvested-energy powered energy-aware access window with grouping strategy algorithm is proposed to cluster dense devices to improve energy efficiency and guarantee the target data rate by taking account of uncertain amount of energy in each device.

Chapter 6

Priority-aware Channel Access Control

This chapter focuses on a priority-aware channel access control for IEEE 802.11ah based time-critical networks to improve access efficiency and energy efficiency. A novel prioritised channel access mechanism is proposed for different priority packets to improve delivery ratio for high-priority packets. Furthermore, a priority-aware access window algorithm is presented to set adaptive window size based on new prioritised channel access mechanism to optimise energy efficiency. Section 6.1 presents the motivation of priority-aware channel access control for IEEE 802.11ah. Section 6.2 proposes the novel prioritised channel access mechanism. In Section 6.3, the new channel access mechanism is formulated. The performance of prioritised channel access mechanism is given in Section 6.4. Section 6.5 presents the priority-aware access window algorithm to optimise energy efficiency for IEEE 802.11ah.

6.1 Motivation

Supporting priority is a main method to provide time-critical information exchange. For example, in forest monitoring system, the information from the humidity monitor is significant for environment and fire preventing [SMTS17], while some other messages from meters to sense the tree health are less latency-limited, although it is a critical parameter for evaluating urban ecosystem health and sustainability [XM05]. The priority of the message affects the efficiency in time-critical networks, where the high-priority packets need to be transmitted timely, however, it has not well realised in current Wi-Fi networks [PSTN08][PZL⁺17][BPF16]. Thus, a prioritised channel access mechanism is required in IEEE 802.11ah networks. In the following work, the priority-aware channel access control is proposed, including a prioritised channel access mechanism to support priority in IEEE 802.11ah, and a priority-aware access window algorithm to maximise energy efficiency via adaptive window size based on the proposed prioritised mechanism.

6.2 System Model

An IEEE 802.11ah network as one AP with 6000 devices is considered. The devices are randomly clustered into several groups. Each group is assigned to a RAW to access channel. In IEEE 802.11ah uplink communications, for each RAW, there are M time slots and N devices limited by lowest and highest AID of devices indicating the location, traffic, type, and energy saving mode [KLKG15].

6.2.1 RAW Operation

In IEEE 802.11ah uplink communications, the devices which have buffered data for the AP randomly select one of the uplink time slots in their allocated RAW and attempt to access the channel. To support the priority, a novel prioritised channel access mechanism is proposed to improve access efficiency by sparing more chances for high-priority packets.

The collision probability for high-priority packets is reduced. The detailed access process via RAW is shown in Fig. 6.1.

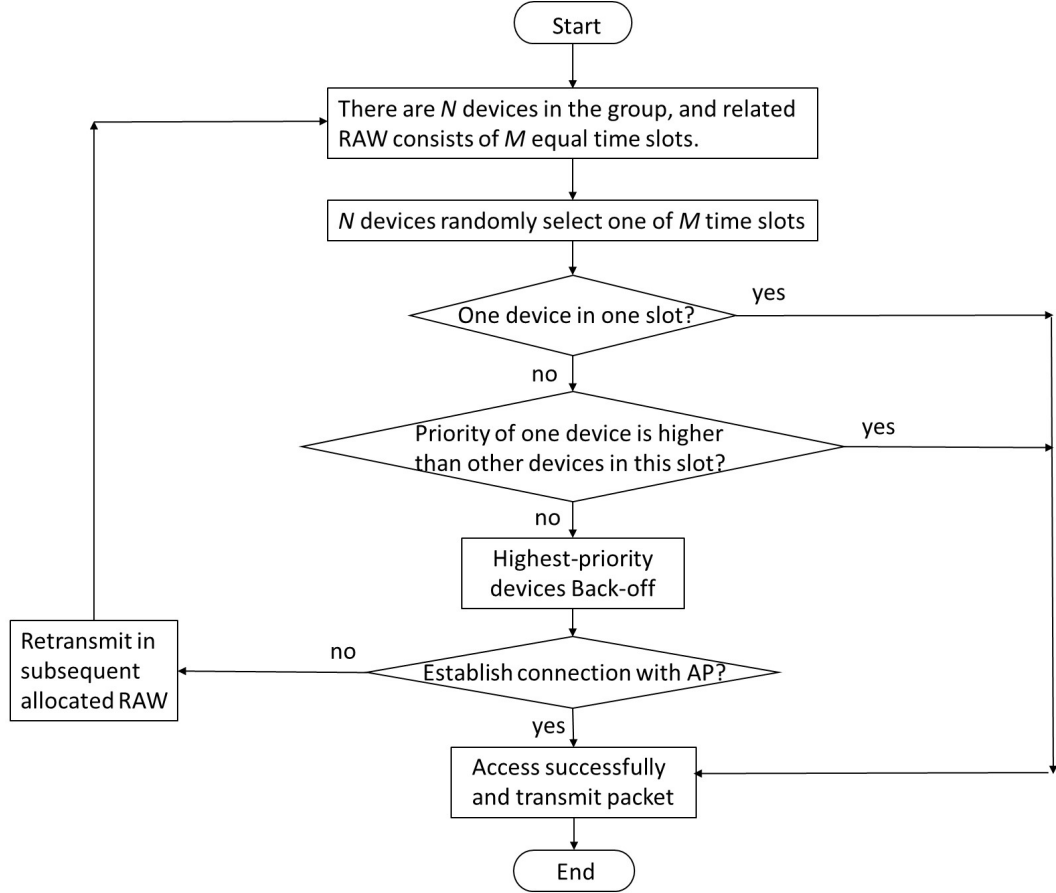


Fig. 6.1: Uplink channel access in IEEE 802.11ah with priority.

As an example shown in Fig. 6.2, after random selection, if there is only one device choosing a slot, it can access the channel directly, for example, Device 1 transmits the packet without contention in Slot 1, ignoring the device priority classification, and the same for Device 3 in Slot 3 and Device $N(j) - 2$ in Slot $M(j)$, which is the same as the standard operation. When there are more than one devices choosing the same time slot, for example, Device $N(j) - 5$ and Device $N(j)$ in slot 2. Different from standard operation that all devices in this slot need to contend through back-off, as the packet priority of Device $N(j)$ is higher than that of Device $N(j) - 5$, Device $N(j)$ can access channel

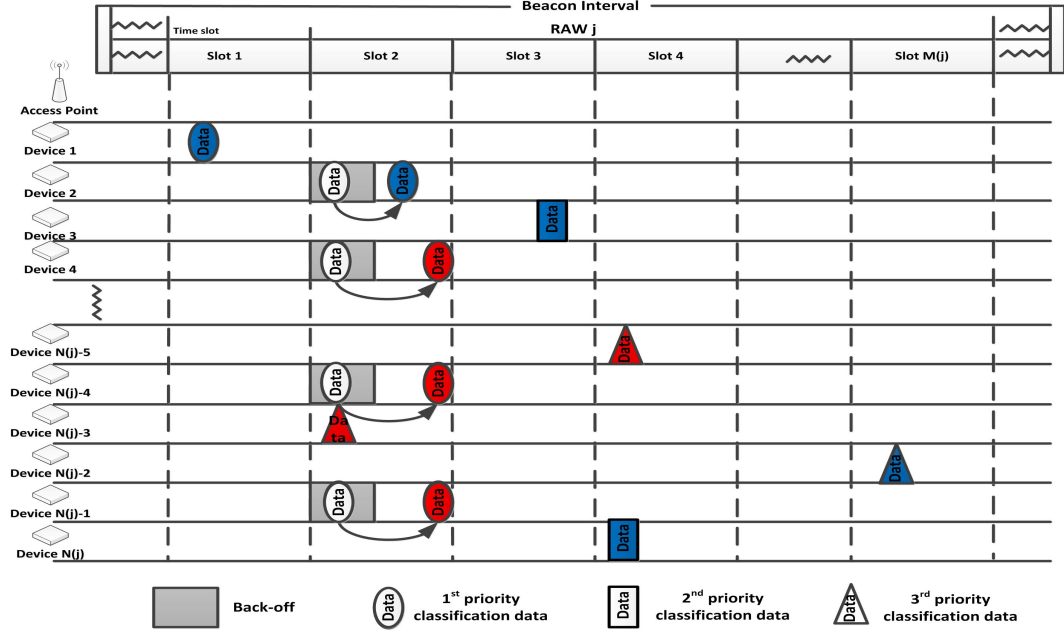


Fig. 6.2: Example of uplink RAW operation in IEEE 802.11ah with priority.

directly while Device $N(j) - 5$ needs to re-attempt to access channel in the next allocated window. For another case, Device 2, Device 4, Device $N(j) - 4$, Device $N(j) - 3$ and Device $N(j) - 1$ in Slot 3, as the priorities of four devices (2, 4, $N(j) - 4$ and $N(j) - 1$) are higher than others, these four devices would come into the back-off stage (signed as grey in Fig. 6.2) to avoid collision by doubling contention window and trying again until reaching the slot boundary. Device 2 accesses the channel successfully in the back-off stage, so Device 2 transmits uplink data to the AP, while Device 4, Device $N(j) - 4$, Device $N(j) - 3$ and Device $N(j) - 1$ need to re-transmit in the subsequent allocated window. If accessing the channel successfully, device requests uplink communications by sending a PS-poll message to the AP. The AP responds with an ACK to confirm the connection. After the first handshake, the device transmits buffered uplink data frame and waits for the ACK from the AP after a SIFS period.

The process is repeated, one RAW by one RAW, until the end of beacon frame as shown in Fig. 2.3.

6.2.2 Channel Condition

In the communication system, the budget is composed of all gains and losses due to distance, fading and shadowing [HRV12]. The main principal link budget equation of the system is denoted by

$$\bar{P}_{RX} = \bar{P}_{TX} + G_{TX} - L_{TX} - PL(l) + G_{RX} - L_{RX}, \quad (6.1)$$

where \bar{P}_{RX} and \bar{P}_{TX} are the receiver and transmitter power; G_{TX} and G_{RX} are the antenna gains at the transmitter and receiver; L_{TX} and L_{RX} are the system losses at the transmitter and receiver; and $PL(l)$ is the path loss in dB at distance l .

The path loss of outdoor scenarios is based on the Macro Deployment or Pico/Hot Zone Deployment. When the antenna height is assumed 15m above rooftop and the path loss in dB is

$$PL(l) = 8 + 37.6 \log_{10}(l); \quad (6.2)$$

when the antenna height is assumed at rooftop level, the path loss is

$$PL(l) = 23.3 + 37.6 \log_{10}(l), \quad (6.3)$$

where l is in meters and the RF carrier frequency is assumed to be 900 MHz. For an other frequency f , a correction factor of $21 \log_{10}(\frac{f}{900})$ should be added [HRV12][A⁺01].

6.3 Problem Formulation

In this section, the uplink transmission probability is formulated for the prioritised channel access mechanism for IEEE 802.11ah.

Based on the existing IEEE 802.11ah channel access [PHL14], there are two success-

ful cases of novel prioritised channel access mechanism for a device to transmit uplink packet.

- Case 1: the time slot is selected by one device. Thus this device could occupy the whole slot to transmit packet directly without contention while ignoring the priority classification
- Case 2: the time slot is selected by multiple devices.
 - Case 2.1: the priority of one device is higher than any other devices in this slot. So this device can access channel directly.
 - Case 2.2: there are more than one device with the top priority. The devices with highest priority will come into the back-off stage to avoid collision by doubling contention window. In addition, the collision does not occur if one of the devices could access the channel in the first back-off stage.

It is assumed that there are C classifications of priority for devices in a group, and each classification contains n_c devices in one group. So the number of devices in one group is the sum of devices in each class as $N = \sum_{c=1}^C n_c$.

Case 1 is the state without contention as there is only one device in one slot after random selection. This device can transmit the packet directly. So the transmission probability for one device in Case 1 is that no other devices choose the slot that is selected by this device, denoted as

$$P_1 = \left(1 - \frac{1}{M}\right)^{N-1}, \quad (6.4)$$

where M is the number of time slots contained in one uplink RAW; N is the number of devices in one group that can attempt to access channel in one uplink RAW.

Case 2.1 is the state that after random selection, the device chooses a slot with

other devices with lower priority, thus this device can access channel directly based on prioritised channel access mechanism. The probability for a device in such case is

$$P_{2.1} = \sum_1^C \frac{n_c}{N} (1 - \frac{1}{M})^{(n_c-1)} (1 - \frac{1}{M})^{(N - \sum_{x=1}^{c-1} n_x)} (1 - (1 - \frac{1}{M})^{(\sum_{x=c+1}^C n_x)}), \quad (6.5)$$

where c is the priority index; n_c is the number of devices of c th priority class in the group.

For Case 2.2, there are several devices with the same highest priority in a certain slot, and one of these devices accesses channel through the first back-off stage.

The probability for multiple (i and $i > 1$) devices with same priority to choose a same slot is

$$P(i) = \binom{N}{i} (\frac{1}{M})^i (1 - \frac{1}{M})^{N-i}. \quad (6.6)$$

So the probability of more than one device in the same priority to choose the same slot is $P_{>1} = \sum_{i=2}^{n_c} P(i)$.

These i devices in the same slot will go to the back-off stage. The probability for one device to build connection with AP through the minimum contention window as first back-off stage is obtained as this device occupies the front slot alone, shown as

$$P_{back-off}(i) = \sum_{x=0}^{W_{\min}-1} \left\{ \prod_0^x \left[1 - \frac{1}{W_{\min}} (1 - \frac{x}{W_{\min}})^{i-1} \right] \right\} \frac{1}{W_{\min}} (1 - \frac{x+1}{W_{\min}})^{i-1}, \quad (6.7)$$

where W_{\min} is the minimum size of the contention window for the back-off mechanism.

Thus in terms of Case 2.2, the overall probability for one device contending with others in a time slot and accessing the channel successfully is as

$P_{2.2} =$

$$\sum_1^C \frac{n_c}{M} \sum_{i=2}^{n_c} \binom{n_c}{i} \left(\frac{1}{M}\right)^i \left(1 - \frac{1}{M}\right)^{n_c-i} P_{back-off}(i) \left(1 - \frac{1}{M}\right)^{\left(N - \sum_{x=1}^{c-1} n_x\right)} \left(1 - \left(1 - \frac{1}{M}\right)^{\left(\sum_{x=c+1}^C n_x\right)}\right). \quad (6.8)$$

Thus, the overall transmission probability for one device to transmit one packet with a RAW is the sum of two cases, which is denoted by

$$P = P_1 + (P_{2.1} + P_{2.2}). \quad (6.9)$$

6.4 Performance Analysis of Prioritised Channel Access

In this section, the proposed prioritised channel access mechanism in IEEE 802.11ah networks is evaluated in Matlab.

An outdoor IEEE 802.11ah network is considered as described in the system model. Each window is assigned to a group of devices to attempt accessing. The nodes in the scenario is following normal distribution, which means more devices are close to AP and less devices in the boundary of scenario. For each RAW, there is only one group of devices being allocated. For the proposed prioritised channel access mechanism, all the devices are divided into three classifications in the simulation, each class with same number of devices. The existing access scheme dose not take packet priority into consideration. All the packets are under the same contention condition, which is if one device is in one slot after random selection, the device could access channel without contention, otherwise, the devices in the same slot would go to back-off stage and the successful state is that some devices could access the channel during the first back-off stage as that of Chapter 3 [PHL14]. The uplink packet delivery ratio and energy efficiency are simulated under various window sizes (the number of slots per window) for a group. The other main

simulation parameters are given in Table 6-A.

Table 6-A: Simulation Parameters for Performance Analysis for Prioritised Channel Access in IEEE 802.11ah Uplink Communications

Parameter	Value	Parameter	Value
Frequency	0.9 GHz	Data rate	100 kbps
Number of devices per group	100	Beacon interval	15 s
Slot duration	31.1 ms	Packet length	1024 bits
Min contention window	8	Max contention window	1024

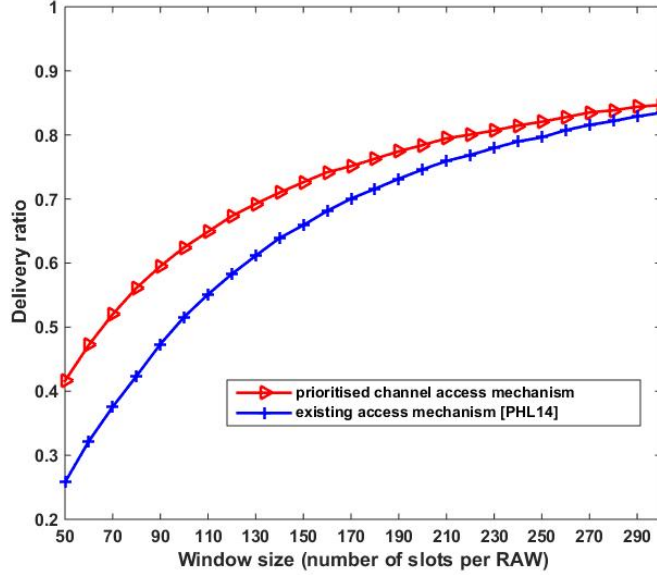


Fig. 6.3: Packet delivery ratio comparison per RAW with different RAW sizes between prioritised channel access mechanism and existing window in [ZWZL13].

Fig. 6.3 shows the packet delivery ratio comparison varying over diverse the window sizes for each group. It can be observed that the proposed prioritised channel access mechanism outperforms the existing access mechanism [PHL14] with 17% improvement with the reason that the proposed mechanism increases the transmission probability when multiple devices choose the same slot after random selection. The prioritised channel access mechanism decreases the contention and gives more chances for packet with higher priority to access the channel. Along with increment of the number of win-

dow size, the trend of delivery ratio goes up with the reason that the collision probability will decrease. In other words, larger window provides more options for devices to choose. Besides, packet delivery ratio improvement between proposed mechanism and the existing mechanism decreases with the growing of window size. For a certain group, the number of states that one slot is chosen by one device will rise, however, the proposed mechanism can decrease contention for multiple devices in one slot. Thus the advantage of proposed one is more obvious for a short window, which can also bring low waiting time for device as a main factor for time-critical communications.

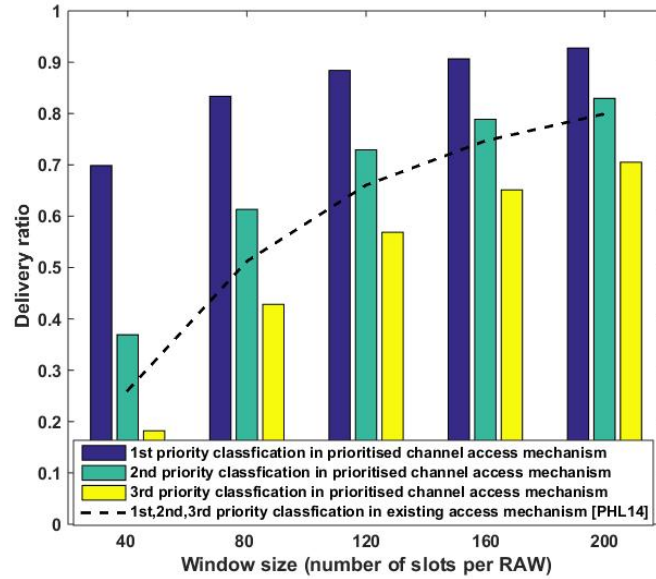


Fig. 6.4: Packet delivery ratio comparison per RAW with different RAW sizes for three priority classifications between prioritised channel access mechanism and existing window in [ZWZL13].

Fig. 6.4 shows the delivery ratio comparison of the first/second/third priority classification packets varying over diverse window sizes for each group. The delivery ratio of the proposed prioritised channel access mechanism is 29% higher than the existing access mechanism in [PHL14] for first classification, 16% higher for second classification, while 27% lower for third classification. All trends are going up along with the increment of the number of slots per window as the collision probability will be lower. The

prioritised channel access mechanism offers more resources for high-priority when more than one devices need to contend in one slot. For the first classification, the growth between two mechanisms is 180% when the window size is 40 slots per RAW since the contention is fierce for small window, thus demonstrating the proposed mechanism leads to lower collision for highest-priority packets. With less contention for a big window, the improvement is not so obvious. The trend of the second classification is similar to that of the first classification except for limited improvement, because the proposed mechanism is more beneficial for the high priority packet. As for the third classification, the new mechanism reduces the access opportunity for low-priority packets, while the existing one can not support priority (regarding all packets as the same one), so the proposed mechanism sacrifices the transmission ratio for the low-priority packets to increase the delivery ratio for the overall network and high-priority packets.

Simulation results demonstrate that the proposed prioritised channel access mechanism can bring superior packet delivery ratio in uplink communications especially under high contention.

6.5 Priority-aware Channel Access Control

6.5.1 Problem Formulation

In this section, the energy efficiency maximisation problem is formulated for IEEE 802.11ah communications based on prioritised channel access. The objective function is derived from transmission probability, energy consumption and throughput.

The energy consumption is related to the data rate and distance between devices and AP, as higher energy is required for higher data rate and longer distance.

Based on Shannon Equation, the received power of a packet is evaluated with data

rate and bandwidth as

$$(\frac{\overline{P}_{RX}}{\overline{N}})_{dB} = (\frac{E_b}{\overline{N}_0})_{dB} + 10\log_{10}(\frac{\overline{C}}{B}), \quad (6.10)$$

where $\frac{E_b}{\overline{N}_0}$ is the ratio of the required energy per bit to the noise power density; \overline{N} is the received noise power; \overline{N}_0 is the Thermal noise power density; \overline{C} is the bit rate and B is the bandwidth.

The received noise power can be denoted as

$$\overline{N} = \overline{N}_0 B = k_b T_0 F B, \quad (6.11)$$

where k_b is the Boltzmann's constant (Joule/Kelvin); T_0 is the receiver temperature in Kelvins (typically set as 293 K) and F is the receiver noise figure.

To obtain $\frac{E_b}{\overline{N}_0}$, bit error rate needs to be considered. The relationship between packet error rate and bit error rate is

$$PER = 1 - (1 - BER)^\gamma, \quad (6.12)$$

where PER is the packet error rate, while BER is the bit error rate. γ is the packet size in bit [HRV12].

In AWGN channel, bit error rate can be denoted as

$$BER = Q(\sqrt{\frac{2E_b}{\overline{N}_0}}). \quad (6.13)$$

According to link budget, the overall gain due to the channel is

$$(G)_{dB} = G_{TX} - L_{TX} - PL(l) - FM + G_{RX} - L_{RX}, \quad (6.14)$$

where FM is the fade margin.

So Equation 6.10 can be transformed to

$$\left(\frac{\bar{P}_{TX}(l)G}{k_b T_0 F B}\right)_{dB} = \left(\frac{E_b}{N_0}\right)_{dB} + \left(\frac{\bar{C}}{B}\right)_{dB}. \quad (6.15)$$

For BPSK modulation, the $\left(\frac{E_b}{N_0}\right)_{dB}$ in AWGN channel is 9dB when PER is 10% and packet size is 1024 bits.

According to the four different states (Case 1, Case 2.1, Case 2.2 and collided) that a device may fall into, the energy consumption for accessing and transmitting for a device to transmit a single uplink packet in j th RAW with M time slots can be denoted as

$$E_t = (P_1 + P_{2.1})P_{TX}(l) + P_{2.2}2P_{TX}(l) + (1 - P)2.5P_{TX}(l) + M\tau E_{wake-up}, \quad (6.16)$$

where l is the distance between a certain device and AP; $(1 - P)$ is the probability for one device falling in the collided state; $E_{wake-up}$ is the idle listening energy for a device in the period of one time slot, which is the energy consumed to support the device in the wake-up mode and τ is the time duration of one uplink slot.

The size of RAW also has the impact on the energy consumption of transmitting signalling information, because for a short RAW duration, the signalling information of AP to each device will be high due to the scheduling information that needs to be transmitted multiple times in a short time. If the group size is small, it also needs massive scheduling information to realise network communications. So the energy consumption of signalling information is related to N and M :

$$E_{signal} = \frac{\alpha}{M} \times \frac{\beta}{N}, \quad (6.17)$$

where α is the parameter indicating the network traffic about the whole amount of data that needs to exchange in this network and β is the parameter to describe the total number of devices in the scenario.

The overall energy consumption consists of transmitting power and signalling energy during uplink RAW, which can be formulated as

$$E_{overall} = N(E_t + E_{signal}). \quad (6.18)$$

Throughput for a RAW is the ratio of number of bits that can be transmitted in one RAW to the RAW duration, which is formulated as

$$R = \frac{N \times P \times \gamma}{\tau M}, \quad (6.19)$$

where $N \times P \times \gamma$ is the total length of packets that can be transmitted for a group with N devices within M time slots. τM is the total time of the one RAW.

Energy efficiency is a main parameter to show efficiency of energy utilisation as the ratio of the throughput to energy consumption. Thus energy efficiency for jth window is

$$EE(M, N) = \frac{R}{E_{overall}} = \frac{\gamma P}{\tau M(E + E_{signal})}. \quad (6.20)$$

For P , E_t and E_{signal} built by N and M , uplink energy efficiency is a function related to group size and window size for IEEE 802.11ah based network.

6.5.2 Priority-aware Access Window Algorithm

In this section, a priority-aware access window algorithm is proposed to optimise energy efficiency for uplink IEEE 802.11ah communications.

The main part $f(M)$ of uplink energy efficiency along with various number of time slots in one uplink RAW (M) can be denoted by

$$f(M) = \frac{P}{M\tau[E_t + E_{signal}]} \quad (6.21)$$

Since P_1 , $P_{2,1}$ and $P_{2,2}$ can be regarded as binomial distribution, when N is large (i.e., $N \geq 20$), the expressions for the probability of two cases can be approximated by the Poisson distribution as

$$P_1 = Ne^{-\frac{N}{M}}, \quad (6.22)$$

$$P_{2,1} = \sum_1^C \frac{n_c}{N} (n_c e^{-\frac{n_c}{M}} (N - \sum_{x=1}^{c-1} n_x + 1) e^{-\frac{N - \sum_{x=1}^{c-1} n_x + 1}{M}} (1 - (\sum_{x=c+1}^C n_x + 1) e^{-\frac{\sum_{x=c+1}^C n_x + 1}{M}})). \quad (6.23)$$

$$P_{2,2} =$$

$$\sum_1^C \frac{n_c}{N} \sum_{i=2}^{n_c} \frac{(\frac{n_c}{M})^i e^{-\frac{n_c}{M}}}{i!} P_{back-off}(i) (N - \sum_{x=1}^{c-1} n_x + 1) e^{-\frac{N - \sum_{x=1}^{c-1} n_x + 1}{M}} (1 - (\sum_{x=c+1}^C n_x + 1) e^{-\frac{\sum_{x=c+1}^C n_x + 1}{M}}). \quad (6.24)$$

So based on the Poisson distribution, the $f(M)$ can be expressed as

$$f(M) = \frac{Ne^{-\frac{N}{M}}}{\tau[(M)^2 \tau E_{wake-up} - 1.5MN\bar{P}_{TX}(l)e^{-\frac{N}{M}} + M2.5\bar{P}_{TX}(l)]}. \quad (6.25)$$

One of the main factors to show concavity and convexity of a function is the second order derivation. Through calculation, the result of second order derivation of $f(M)$ can

be simplified as

$$f''(M) = \frac{e^{\frac{-N}{M}} N^2 \ln e(N \ln e - 2M)}{\tau M^4 [2.5 \bar{P}_{TX}(l)M - 1.5 \bar{P}_{TX}(l)MN e^{\frac{-N}{M}} + \tau E_{wake-up}(M)^2]}, \quad (6.26)$$

which is negative as $(N \ln e - 2M) < 0$ and $2.5 \bar{P}_{TX}(l)M - 1.5 \bar{P}_{TX}(l)MN e^{\frac{-N}{M}} > 0$, indicating it is a concave curve with one maximum point along different uplink RAW sizes.

The optimal RAW duration for uplink communications to optimise energy efficiency by applying Gradient Descent approach, a fast algorithm to find the optimum of large search space as shown in Algorithm 10.

Algorithm 10 is a standard Gradient Descent approach to find the optimal window size based on the novel prioritised channel access mechanism. The algorithm begins with an arbitrary window size, and then gradient is calculated as the value that is required to add to the input. The comparison is done for the current and updated results. The updated solution is acceptable when the gap is positive, otherwise, reserve the previous one. The optimal window size is searched by the iteration.

6.5.3 Simulation Results

In this section, the proposed priority-aware access window algorithm for IEEE 802.11ah based IoT networks is evaluated in Matlab. An outdoor IEEE 802.11ah network as one AP surrounded by 6000 devices is considered as described in system model. Macro deployment is applied as the antenna height is 15m above the rooftop. Each window is assigned to a group of devices to access. The nodes in the scenario is following normal distribution, which means more devices close to AP and less proportion of devices in the boundary of scenario. Each involved device has exactly one packet to transmit for uplink communications during a RAW. The optimal value is found based on the setting of 200 to α and β respectively. The uplink energy efficiency is simulated under various

Algorithm 10 Gradient Descent Priority-aware Access Window Algorithm

-
- 1: **Step 1:** AP recognises the group size (N), the priority classification (C) and the distance between device and AP (l).
 - 2: **Step 2:** Transmit power is determined according to packet error rate, signal modulation mode, distance between device and AP, required data rate and bandwidth.
 - 3: $(\frac{P_{TX}(l)G}{k_b T_0 F B})_{dB} = (\frac{E_b}{N_0})_{dB} + (\frac{\bar{C}}{B})_{dB}$
 - 4: **Step 3:** Estimate optimal uplink RAW size for a certain group.
 - 5: **loop**
 - 6: Initialise M_{old} and M_{new} as two random numbers.
 - 7: $EE'(M) = \frac{\partial(-EE(M,N))}{\partial M}$
 - 8: **while** $|EE(M_{old}) - EE(M_{new})| \geq precision$ **do**
 - 9: $\partial = 0.01$
 - 10: $M_{old} = M_{new}$
 - 11: $M_{new} = M_{old} - \partial \times EE'(M)$
 - 12: **end while**
 - 13: return M
 - 14: **end loop**
 - 15: **Step 4:** AP sets the window size as M equal time slots for jth group. The devices in this group fall into sleep mode and wake up until coming to their allocated window.
 - 16: **Step 5:** N devices in the group try to establish connection with AP by randomly selecting one of M time slots in RAW and attempt to access the channel.
 - 17: N devices in the group choose one of M slots randomly.
 - 18: Devices attempt to access channel to establish connection with AP as Case 1 and Case 2. When only one device in one slot, the device accesses channel directly without contention; when multiple devices in one slot, the device with highest priority to contend and attempt to access medium.
 - 19: When the device could not access in its slot, re-attempt in the next allocated window.
-

number of devices per group. The main simulation parameters are given in Table 6-B.

First, the scenario with three priority classifications are simulated and analysed. For priority, all the devices are divided into three classifications, each class with the same number of devices.

Fig. 6.5 shows the energy efficiency comparison varying over group sizes when there are three classes of priority. The trends of all three curves under three different conditions are concave with a peak point. It can be observed that the proposed RAW improves by

Table 6-B: Simulation Parameters for Priority-aware Access Window in IEEE 802.11ah Uplink Communications

Parameter	Value	Parameter	Value
Frequency	0.9 GHz	Data rate	100 kbps
$G_{TX}(dBm)$	0	$G_{RX}(dBm)$	3
Noise figure (dB)	3	Fade Margin (dB)	10.3
Modulation	BPSK	PER	10%
Bandwidth	2 MHz	Idle listening power	0.001 mw
Total number of devices	6000	Average distance	300 m
Packet size	1024 bits	Time slot duration	31.1 ms
Min contention window	8	Max contention window	1024

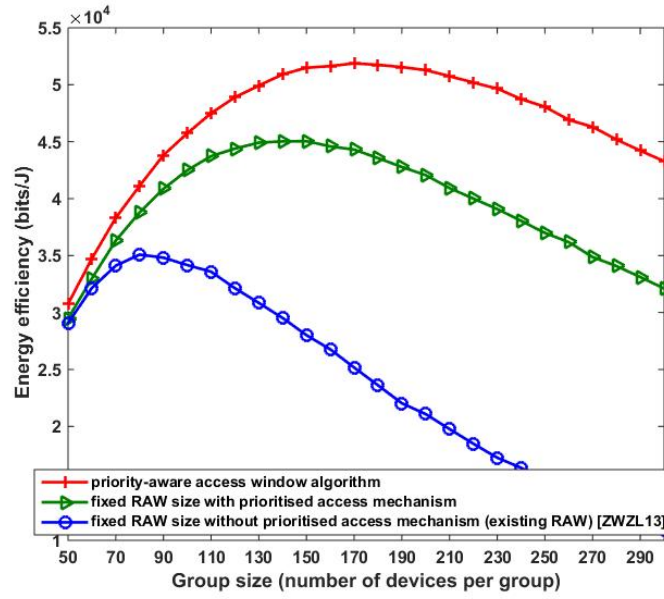


Fig. 6.5: Energy efficiency comparison per RAW with different group sizes among priority-aware access window algorithm, fixed RAW size with prioritised access mechanism and existing window in [ZWZL13].

around 112% and 23% when comparing with that of the fixed window without prioritised access mechanism in [ZWZL13] and the fixed window with prioritised access mechanism respectively. For the fixed window size, the peak point is at 80 devices per group for the conventional access mechanism and at 150 devices per group for the proposed prioritised access mechanism, while that of the priority-aware access window algorithm is at 170

devices in one group, as the prioritised access mechanism can decrease the contention for dense networks and the dynamic window changes its size according to the group size. So for a larger group, the window size would enlarge to accommodate more devices to access.

For a small group size, the signal energy consumption would be high to achieve the whole network communications since scheduling information would be sent multiple times after a short time to achieve the whole network communication. Since the contention for small number of devices per group is low, which means the probability for multiple devices in one slot is low, the improvement for prioritised access mechanism is not obvious. So with the increment of group size, the signalling energy consumption will decrease, which is a dominant factor to increase the energy efficiency, and the collision is higher so that prioritised access mechanism can work to decrease the contention, thus the prioritised access mechanism brings to higher efficiency when comparing with the existing mechanism that could not support priority. However, if the number of devices per group is too large, the collision probability would be high due to high contention that leads to consume more energy and reduce throughput which are two parameters for low efficiency, thus the trend of curves will go down. Both prioritised access mechanism and adaptive window can decrease the level of contention, so the decline rate of the proposed priority-aware access window algorithm is lowest and fixed window without prioritised access mechanism is the worst.

Fig. 6.6 shows the delivery ratio comparison varying over diverse number of devices for each group when there are three classes of priority. The proposed priority-aware access window algorithm performs better than the fixed window with conventional access mechanism in [ZWZL13] with 250% improvement and the fixed window with prioritised access mechanism with around 62.5%. The packet delivery ratio goes down with the increment of group size, as the contention is higher for a group with more devices so that the collision probability would increase. In detail, for a certain RAW, fewer devices lead to less contention which results in a higher transmission probability. The priori-

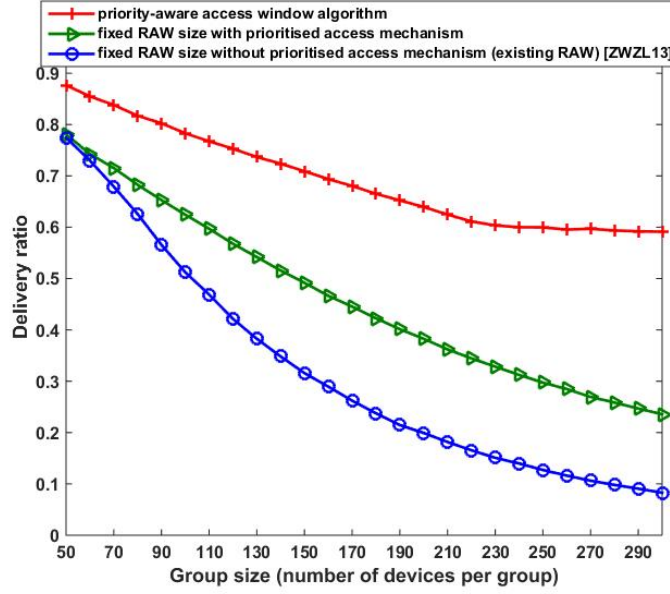


Fig. 6.6: Packet delivery ratio comparison per RAW with different group sizes among priority-aware access window algorithm, fixed RAW size with prioritised access mechanism and existing window in [ZWZL13].

tised access mechanism decreases the collision by sparing more resources for high-priority packets to guarantee them that they could be delivered, so the delivery ratios of two scenarios with novel prioritised access mechanism are higher than the one with the existing access mechanism, and the dropping speed is lower. The window size of the proposed priority-aware access window algorithm is larger for a large group, which can alleviate the collision probability, thus the rate of decreasing for the proposed window is lower than the existing window.

Fig. 6.7, Fig. 6.8 and Fig. 6.9 show the delivery ratio comparison of the first/second/third priority classification packet varying over diverse group sizes respectively under the circumstance that there are three classes of priority. The delivery ratio of the proposed priority-aware access window algorithm is higher than the other two scenarios, while the fixed window with the prioritised access mechanism performs better than the fixed window with the existing access mechanism in [ZWZL13] in first/second priority class but worse in third class. All nine curves are going down along with increment of the

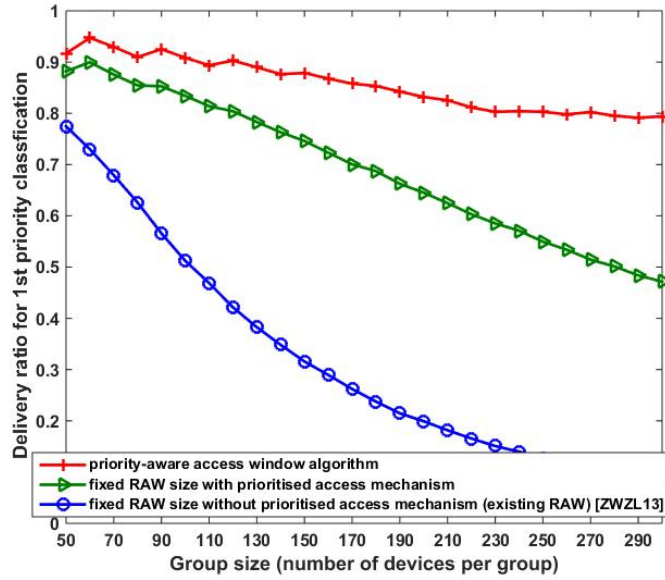


Fig. 6.7: Packet delivery ratio comparison per RAW for the first priority classification with different group sizes among priority-aware access window algorithm, fixed RAW size with prioritised access mechanism and existing window in [ZWZL13].

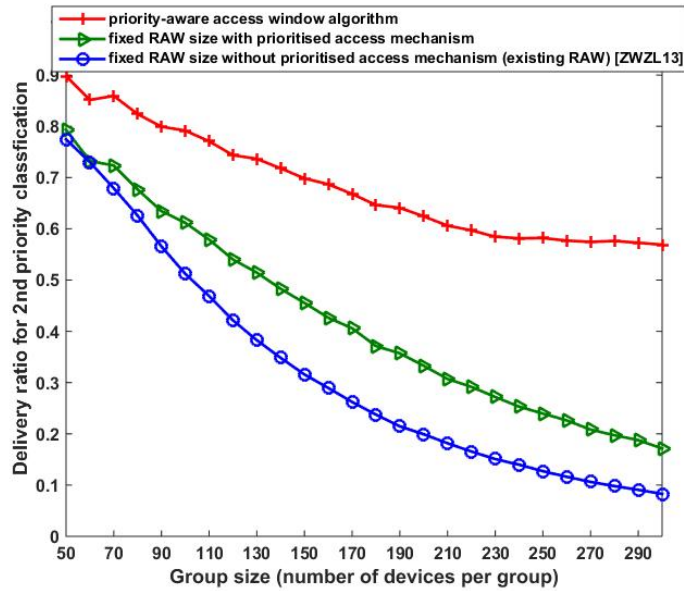


Fig. 6.8: Packet delivery ratio comparison per RAW for the second priority classification with different group sizes among priority-aware access window algorithm, fixed RAW size with prioritised access mechanism and existing window in [ZWZL13].

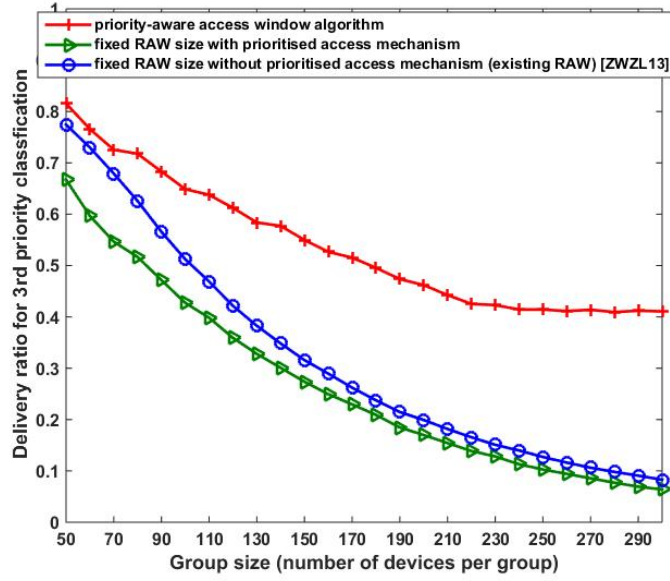


Fig. 6.9: Packet delivery ratio comparison per RAW for the third priority classification with different group sizes among priority-aware access window algorithm, fixed RAW size with prioritised access mechanism and existing window in [ZWZL13].

group size as the collision probability is higher. The prioritised access mechanism offers more resources for the high-priority packets when more than one devices need to contend in one slot. In addition, the adaptive window alleviates contention through enlarging the window size for a large group. Hence the delivery ratio of proposed priority-aware access window algorithm is the highest. For the first classification, the gap between three scenarios are growing along window sizes since the contention is fierce for a large group, thus the proposed prioritised access mechanism leads to lower collision for the highest priority packet. With less contention in a small group, the improvement is not obvious. The second classification is similar to the first except for limited improvement, because the proposed control is more beneficial for high-priority packets. As for the third classification, the new prioritised access mechanism reduces the opportunity to access as the packets are with lower priority compared to the other two classes of packets, while the existing one can not support priority (regarding all packet as same one), so the proposed prioritised access mechanism sacrifices the transmission ratio for the low-priority packets

to increase the delivery ratio for the overall network and higher priority packets. Thus the high-priority packets can be transmitted timely with high probability in priority-aware access window to make the time-critical applications more efficient.

The influence of priority distribution is analysed with different proportions of three classifications. Four scenarios are compared as (1st class: 33%; 2nd class: 33%, 3rd class: 33%; 1st class: 50%; 2nd class: 25%, 3rd class: 25%; 1st class: 25%; 2nd class: 50%, 3rd class: 25%; 1st class: 25%; 2nd class: 25%, 3rd class: 50%).

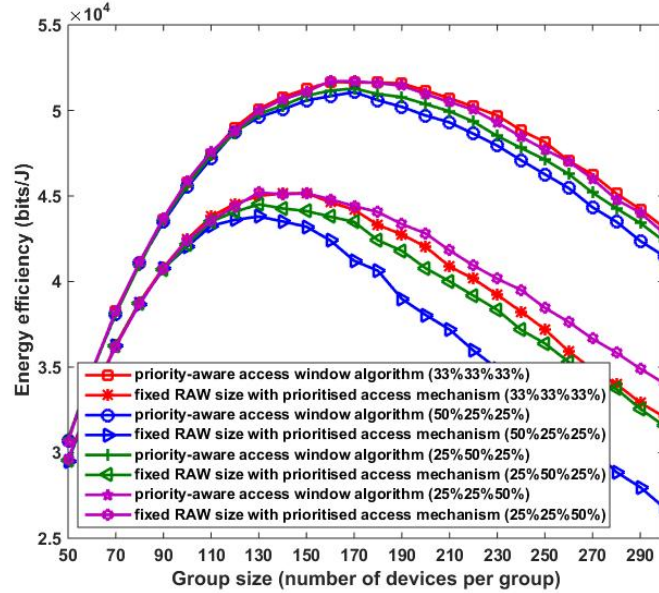


Fig. 6.10: Energy efficiency comparison per RAW with different group sizes under diverse priority distributions (30%30%30%; 50%25%25%; 25%50%25%; 25%25%50%) between priority-aware access window and fixed RAW size with prioritised access mechanism.

Fig. 6.10 and Fig. 6.11 show the uplink energy efficiency and delivery ratio comparison varying over four priority distributions. The one under same proportions for three classes (30%30%30%) is the highest in energy efficiency, while the one with more devices in the highest class (50%25%25%) performs worst. As the proposed prioritised access mechanism offers more chances for higher priority devices to access channel, if high con-

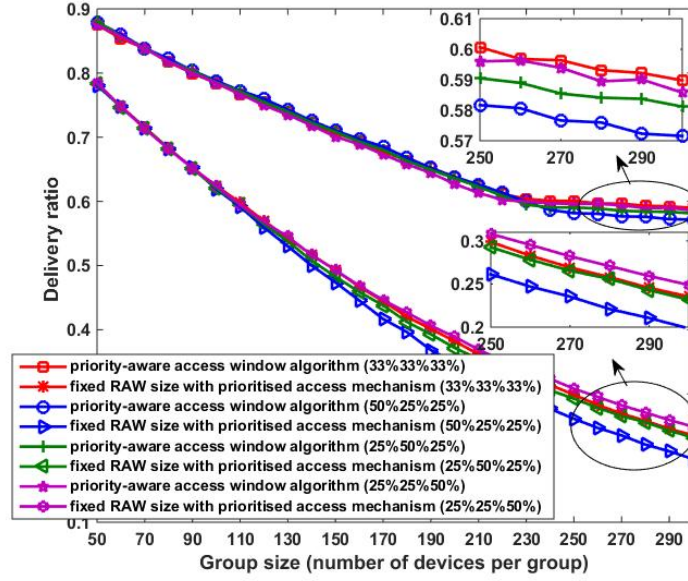


Fig. 6.11: Packet delivery ratio comparison per RAW with different group sizes under diverse priority distributions (30%30%30%; 50%25%25%; 25%50%25%; 25%25%50%) between priority-aware access window and fixed RAW size with prioritised access mechanism.

tention for higher priority devices, the advantage of proposed mechanism can not function well as the scenario that more devices for low priority devices, so the behaviour ranking is $(25\%25\%50\%) > (25\%50\%25\%) > (50\%25\%25\%)$. The pros of access mechanism are not obvious when the number of devices in high classes is too low, so energy efficiency and delivery ratio of the one with (30%30%30%) perform better than the other three.

The performance of different number of priority classifications is evaluated under the scenarios that each class contains same number of devices.

Fig. 6.12 and Fig. 6.13 show the uplink energy efficiency and delivery ratio comparison varying over diverse group sizes for two different priority classifications. $C = 3$ means there are three classes of priority (first, second and third based on the application types), and $C = 4$ represents the the priority is divided into four classes (first, second, third and forth class based on the application types). It can be observed from both

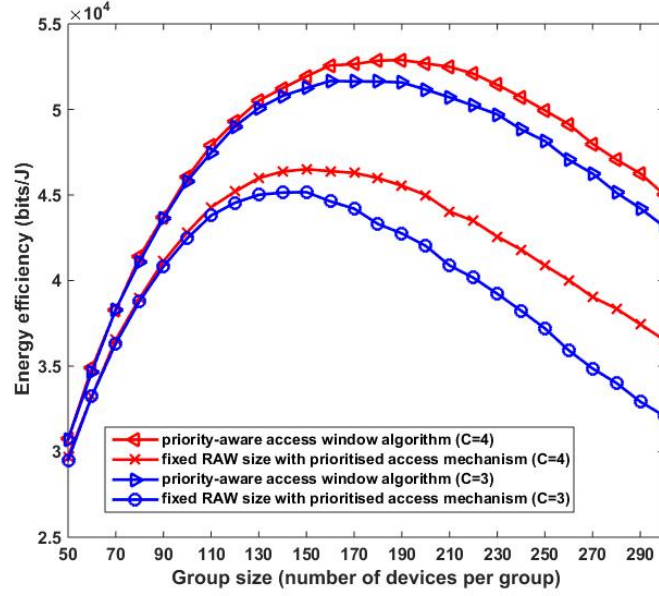


Fig. 6.12: Energy efficiency comparison per RAW with different group sizes under two priority classifications ($C=3$ and $C=4$) between priority-aware access window and fixed RAW size with prioritised access mechanism.

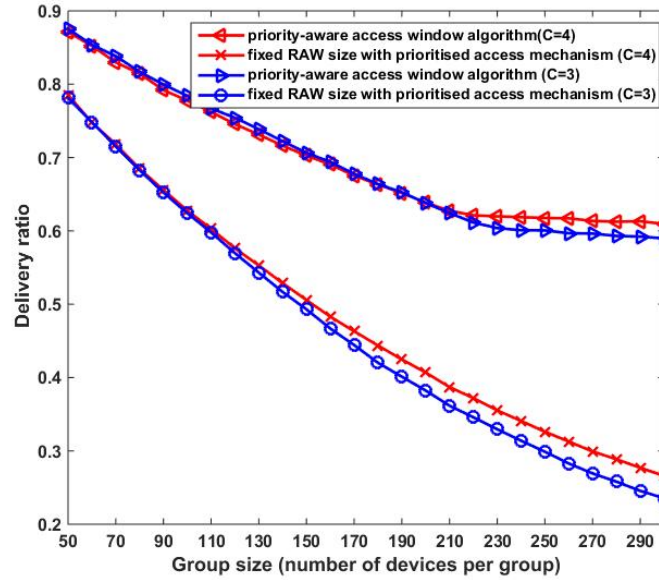


Fig. 6.13: Packet delivery ratio comparison per RAW with different group sizes under two priority classifications ($C=3$ and $C=4$) between priority-aware access window and fixed RAW size with prioritised access mechanism.

figures that the scenarios with $C = 4$ performs better than that of $C = 3$ for energy efficiency and delivery ratio, hence refining classification makes the performance better. The curves of the energy efficiency are concave with the same reason of Fig. 6.5, and curves of delivery ratio are going down as Fig. 6.6. The behaviours are similar regarding different classifications (3 or 4) for small groups. The reason is that when the number of slots in one group is limited, the contention level is low so that the state of multiple devices in one slot is in low probability to appear, thus the pros of novel priority-aware access window is not obvious. But the improvement of $C = 4$ is higher for bigger group sizes, as more classes of priority lead to decrease the valid contention devices in one slot, resulting in lower collision probability, which is the dominant factor for high energy efficiency and delivery ratio. Besides, based on low contention from priority-aware access window, the number of slots of RAW can be decreased which can reduce the power for wake-up mode, acting as an element for better energy efficiency. So for a large group, increasing the total number of priority classification could lead to higher energy efficiency and delivery ratio.

Simulation results demonstrate the proposed priority-aware access window can bring superior energy efficiency and delivery ratio for IEEE 802.11ah uplink communications. In addition, the high-priority packet can be delivered in higher ratio than others, which is beneficial for time-critical networks.

6.6 Summary

In this chapter, the prioritised channel access mechanism is proposed to limit the collision for high-priority packets for time-critical networks. The energy efficiency optimisation problem is formulated by probability theory to monitor the access process for different priority classes under the novel prioritised channel access mechanism. The energy consumption is evaluated for various accessing states. Apart from that, the distance between

devices and AP, data rate, and modulation mode are also considered in the energy consumption model. On account of that, the overall energy consumption and throughput are estimated to contribute to the energy efficiency. The priority-aware access window algorithm is proposed to optimise uplink energy efficiency through adapting RAW duration for different group sizes and diverse device distributions.

Chapter 7

Conclusions and Future Works

7.1 Conclusions

This thesis proposed a novel two-stage adaptive RAW scheme for the IEEE 802.11ah based networks. The proposed scheme aims to improve the energy efficiency by four channel access control blocks in two stages as RAW size control in the first stage, RAW retransmission control, harvested-energy powered access control and priority-aware channel access control in the second stage.

RAW size control in the first stage, as shown in Chapter 3, was proposed to optimise uplink energy efficiency by finding the adaptive window size based on diverse groups of devices. The optimisation problem was built by probability theory to determine the probabilities of various statuses that a device may fall into when transmitting a packet via one RAW. On account of that, the overall energy consumption and throughput were estimated to contribute to energy efficiency. Two algorithms were proposed in RAW size control block, including an energy-aware access window algorithm to improve energy efficiency through adaptive number of slots per window based on various group sizes, and an energy-delay aware access window algorithm to jointly improve energy efficiency

and delay via dynamic number of slots and internal slot duration based on diverse group sizes and application types. The simulation results showed that the dominant factor changed along the group sizes or window sizes, and the proposed control improved the uplink energy efficiency, the delivery ratio and decreased the average delay. So RAW size control enhances the performance of massive access in IEEE 802.11ah based IoT networks through the energy efficiency improvement of battery powered devices.

RAW retransmission control was proposed in Chapter 4 to improve the channel utilisation. A novel retransmission mechanism was presented to alleviate slot waste through retransmitting the collided packets at subsequent slot in the same RAW. The Markov Chain was applied to describe the dependency between adjacent slots. The number of packets that can be transmitted in one slot was estimated by probability theory. Based on that, two algorithms were proposed in RAW retransmission control block, including an energy-aware access window with retransmission algorithm to improve energy efficiency through adaptive number of slots per window based on various group sizes, and an energy-delay aware access window with retransmission algorithm to jointly improve energy efficiency and delay via dynamic number of slots and internal slot duration based on diverse group sizes and application types. The simulation results demonstrated the improvement of proposed control on the uplink energy efficiency, the delivery ratio and the average delay. RAW retransmission control increases the channel utilisations and energy efficiency to save access resource and device access power for resource-constrained IEEE 802.11ah based IoT networks.

Harvested-energy powered access control was proposed to improve energy efficiency and achievable data rate for IEEE 802.11ah energy harvesting networks, in which the devices are equipped with an energy harvester and an energy storage, as presented in Chapter 5. The channel condition and uncertain amount of harvested energy in each devices were considered in this control block to set adaptive window size based on the group size. Apart from that, a grouping strategy was proposed for clustering highly dense

devices to realise achievable data rate. The simulation results showed the proposed control outperformed the existing RAW on the uplink energy efficiency and the delivery ratio for harvested-energy powered networks. Harvested-energy powered access control deals with the uncertainty in energy harvesting networks and improves energy efficiency for the devices with low energy storages to extend the lifetime for IEEE 802.11ah based IoT networks.

Priority-aware channel access control was proposed in Chapter 6 to improve access efficiency for time-critical networks. A novel prioritised channel access mechanism was presented to reduce collision for high-priority packets. Based on that, a priority-aware access window algorithm was proposed to improve energy efficiency via setting adaptive window size by taking consideration of group sizes, the number of priority classes, and priority classification distributions. The simulation results showed the proposed control effectively stressed the access challenge in time-critical networks and improved the access efficiency for high-priority packets, the energy efficiency and the packet delivery ratio. Priority-aware channel access control handles the hierarchical-priority packets in IoT networks to decrease the contention of high-priority packets in time-critical IEEE 802.11ah based IoT networks.

7.2 Future Works

The potential areas for future works include:

- Energy efficient MAC layer management in IEEE 802.11af based networks

In this thesis, special attention is given to IEEE 802.11ah based IoT networks. Potential work can be explored on the network optimisation for IoT applications which is supported by other long-range wireless technologies, such as IEEE 802.11af, a low-cost range-enhanced WLAN for opportunistic use of the sub-1 GHz with more than 1km transmission range [Har14][UYC⁺15]. It defines international specifications for spec-

trum sharing among unlicensed white space devices and licensed services in the TV white space band [FGK⁺13]. As it provides long-range converge for future networks, a potential issue that needs to be addressed is the energy efficient management for channel access with the concern of operating at the white space band.

- MAC management for IEEE 802.11ah networks with privacy

As exponential growth in the deployment of WLAN, privacy and confidentiality issues have become a major concern [AANSH15]. Although IEEE 802.11i designed a mechanisms to improve privacy and confidentiality, it still does not provide sufficient protection for availability and integrity such as denial of service, session hijacking and MAC address spoofing attacks [Mit05]. IEEE 802.11ah supports the future highly dense IoT networks to communicate automatically for several years. Therefore, the channel access management with privacy needs to be investigated in IEEE 802.11ah to adapt to the sensors to mitigate risks of the privacy and confidentiality for IoT applications.

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